Cross-Layer Design of Adaptive Communications Solutions in Wireless Sensor Networks

by

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has lead to the award of a degree.

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Preface

This thesis is submitted to the University of Strathclyde for partial fulfilment of the requirements for the degree of philosophiae doctor.

This doctoral work has been performed at the Department of Electronic and Electrical Engineering, Centre for Intelligent Dynamic Communications (CIDCOM), with Prof John Dunlop as main supervisor and with co-supervisor Dr. James Irvine.

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Abstract

In the actual era of the information digitisation, the technological advances are enabling the development of Wireless Sensor Networks for the observation of physical phenomena in environmental, industrial and commercial domains. The proposed applications require ever larger networks in size and number of nodes that involve the use of multi-hop communications in order to collect information in the base stations (sinks) of the network. Due to the limited energy and radio resources of the sensor nodes and, taking into account the dynamics of such networks in terms of topology, application requirements, congestion access and node failures, the interconnection of such networks into effective systems is extremely difficult in order to achieve the exigent lifetime expectation.

This research focuses on the design of communication protocols directed to increase the adaptability of the network with the aim of managing these network dynamics, congestion and failure problems. The methodology used consists in the co-design of cross-layer solutions that make use of adaptive techniques like smart antennas, hybrid access mechanism and merged Routing-MAC proactive schemes.

The cross-layer developments have been integrated into a flexible communications framework (XLCA) that includes the functionality needed in sensor networks applications. The exercising and evaluation of XLCA has demonstrated the adaptability skills and potential to extend the operational network lifetime of the proposed cross-layer techniques. The results of this research show that the integration of functionality and capabilities of the various communication elements (Routing, MAC and Physical), firstly, allow to adjust the post-deployment nodes operation that enhance the network adaptability and, secondly, optimises the use of radio resources, which consequently increases the longevity of the network.

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List of Abbreviations

ACK	Acknowledgement
ARQ	Automatic Repeat Request
BER	Bit Error Rate
BI	Battery Index
CDMA	Code Division Multiple Access
CH	Cluster Head
CLOI	Cross-Layer Optimization Interface
C-MAC	Contention MAC
CMOS	Complementary Metal–Oxide Semiconductor
CSMA	Carrier Sense Multiple Access
CTS	Clear To Send
CV	Coefficient of Variation
DD	Directed Diffusion
DIAS-MC	Design, Implementation and Adaptation of Sensor Networks through Multi-dimensional Co-design
DIFS	Distributed Inter-Frame Space
EAR	Energy Aware Routing
EI	Efficiency Index
EPSRC	Engineering and Physical Sciences Research Counci
ETX	Expected Retransmissions
EVBT	Energy-Aware Virtual Backbone Tree
FBPA	Four-Beam Patch Antenna
GUI	Graphical User Interface
LEACH	Low Energy Adaptive Clustering Hierarchy
LP	Low Power
LPL	Low Power Listening
LQI	Link Quality Indicator
LRA	Localised Routing Algorithm

MAC	Medium Access Control
MCU	Micro-Controller Unit
MEMS	Micro-Electro-Mechanical Systems
MF	Mobility Framework
NAV	Network Allocation Vector
NpN	Neighbours per Node
OD	OmniDirectional
OMNeT++	Objective Modular Network Testbed in C++
PCB	Printed Circuit Board
PER	Packet Error Rate
PM	Power Management
RSSI	Received Signal Strength Indicator
RTS	Request To Send
SBA	Switched Beam Antenna
SIFS	Short Inter-Frame Space
SLL	Side Lobe Level
SNIR	Signal to Interference-plus-Noise Ratio
SP	Sensornet Protocol
SSAS	Scheduled Sectorial Access at Sinks
TDMA	Time Division Multiple Access
VCT	Vulnerability Checking Time
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Networks
XLCA	Cross-Layer Communication Architecture

List of Symbols

$B_k(t)$	Battery level of node k at time t (mA·s)
$I_k(\square)$	Current drain of node k at time □ (mA)
P_r	Received Power at distance d (mW)
P_r	Transmission Power (mW)
X^σ	Log-normal random factor with standard deviation σ
α	Path loss exponent
λ	Signal wavelength
d	Link distance (metres)
$G_{t/r}(\theta_k)$	Linear gain of the switched beam antenna pattern in the angle θ towards node k in transmission (t) & reception (r)
G_{max}	Maximum gain at the peak beam axis (=num. of sectors)
SLL	Linear gain at the side lobes level (= G_{min})
HPBW	Half-power beamwidth (= 360°/sectors)
n	Number of sectors in the switched beam antenna
k_n	Slot position number k at sector n
$T_{\substack{Tx,Rx,\\ Idle,Switch}}(t)$	Accumulated time of the Transmit (Tx), Receive (Rx), Idle and Switching modes (seconds)
$W_{\substack{Tx,Rx,\\ Idle,Switch}}$	Absolute power consumption per time unit for Tx, Rx, idle and switching modes (mW/s)
D_c	Duty-cycle $[T_{Tx}(t)+T_{Rx}(t)+T_{Idle}(t)+T_{Switch}(t)]\ /\ T_{Sleep}(t)$

Chapter 1

Introduction

Wireless Sensor Networks (WSNs) are becoming increasingly common in the large scale monitoring of physical phenomena, where flexibility, scalability and limited cost make them appropriate in numerous civil and military domains. In the last decade, this wireless technology has witnessed remarkably increasing popularity in both academia and industry with high research activity in diverse fields of engineering. In WSNs, the sensor nodes appear as a straightforward combination of modern technology; together, sensors with microcontroller and wireless communications allow a huge amount of potential applications. Anything from monitoring of environmental conditions to real-time tracking can be done with these large-scale, highly distributed systems of small, battery-powered, unattended sensors and actuators. Not surprisingly, WSN technology has been considered to be one of the "10 Emerging technologies that will change the world" [1]. This chapter reviews the WSN technology and applications, identifies important constraints and design challenges related with this work, and introduces the research context and design of this thesis.

1.1 Wireless Sensor Networks

The power of wireless sensor networks lies in the ability to deploy large numbers of tiny nodes that self-organise themselves by creating multi-hop wireless paths through mutual cooperation. Unlike traditional wired systems, deployment costs are minimal without the need to deploy hundreds of metres of wire. Nevertheless, instead of relying on a pre-deployed infrastructure (WLAN), each individual sensor or actuator becomes part of the overall infrastructure. They work collectively and collaborate together on common tasks of sensing, data-collection, communications and actuation to meet the application requirements and provide good network-wide performance in terms of network life-time, latency, and completeness of the sensed data.

Due to the stringent requirements and limited resources in WSNs, it is essential to investigate and design efficient hardware and software solutions for the sensor nodes. However, actually combining sensors, radios, and microcontrollers into an effective network requires the use of co-design techniques to integrate the hardware system and all dimensions of the software system, across the HW/SW boundary (of particular interest in the DIAS-MC project [2]). Co-design of optimal WSN solutions needs to consider efficient networking technologies for distributed systems, which is dependent on a detailed understanding of the both capabilities and limitations of each of the underlying hardware components. In particular, to date, the radio communications cause the main energy consumption in WSNs [3], and therefore, the design of ultra-low power radio hardware and efficient communication protocols represent the most attractive yet challenging approaches. The communication protocols are also responsible for providing adaptability to support network dynamics such as the introduction of new nodes and for compensating for node failures.

The current state of the art in ultra-low power technologies such as the combination of complementary metal–oxide semiconductor (CMOS) integrated circuitry and microelectromechanical systems (MEMS) [4][5], in addition to energy harvesting techniques [6] and low cost printable batteries [7], allows the miniaturisation process of the hardware components and provide a foundation for autonomous microsystems that compose wireless sensor networks. With the convergence of such hardware technologies and efficient networking protocols the idea of sensor-rich "smart environments" [8][9] are becoming a reality.

1.2 Applications and Functional Requirements

Who would say a quarter of century ago that personal computers or mobile phones were going to have so much success and applications; nowadays it is even possible to pay the shopping with a mobile phone. In many aspects technology is advancing faster than its practical use in real applications. The same is true of sensor networks, although it is still a developing technology, the rapid progress that is being experienced permits many applications with the use of distributed sensors embedded in the physical world. Applications in WSN appear in a variety of domains that have specific functional requirements (what the system needs to do) in order to achieve the user objectives. Some of the proposed applications are:

1. Scientific experimentation and environmental applications involving environment [10], marine [11], animal [12][13], habitat [14] and forest fire [15] *monitoring.*
2. Civil, naval and industrial engineering sensor deployments for measuring structure [16], ships [17] and device [18] *responses.*
3. Commercial and military applications directed at *detection* [19] and *tracking* [20] of objects and phenomena.
4. Building environment or medical applications directed to minimise energy spending [21][22] and increase homes comfort [23] and health of patients [24][25].

Figure 1.1 represents some of these typical WSN applications.

1.2.1 Functional Requirements

From the listed applications and attending to the illustrations in Figure 1.1, it becomes clear the advantage in WSNs of deploying a large number of nodes. Despite the restricted capabilities of a single sensor node, the interconnection of hundreds of them offers a wide range of new technological possibilities. Increasing the number of nodes involved in the WSN offer fundamental benefits to the mentioned sensing applications including: extended range of sensing, fault-tolerance, higher accuracy and lower cost.

Figure 1.1 - WSN Applications. Cattle monitoring. Tracking of containers. Bridge and traffic control. Smart home automation.

Depending on the particular functional requirements, it is possible to differentiate three types of WSN applications in terms of the required communications traffic, temporal response and network topology, such as:

Applications designed for *data collection* and posterior analysis. For example, monitoring of weather and pollution metrics for environmental experiments, soil moisture for precision agriculture, or electrical loads on smart homes. These applications are characterised by relatively static topologies, low data rates and tolerance to delays in data acquisition at the sinks.

Security monitoring applications for events detection, information of the events (alarms) and actuation, if available. For example some important events are fires on buildings and forests, leakages of dangerous substances in industrial applications, unauthorised intruders or the vital signs of a patient. In these applications, typically, the traffic towards the sinks will be very low or null, but the network has to be prepared to instantly detect and forward alarm messages with high reliability.

Therefore the majority of the energy will be used to confirm the correct functionality of the network.

Applications that require monitoring and position *tracking* of things such as vehicles, commercial assets, animals, or soldiers. The particularity of these node tracking applications is the frequent topology changes, with nodes entering and leaving the system, and connectivity disruptions of the nodes being tracked. It is usually required to have nodes at fixed locations in order to guarantee network connectivity and adaptation to the topology changes.

In many applications it is possible, and desired, to combine aspects from these three categories. For example, in a WSN for bridge monitoring (Figure 1.1), the nodes that are intended to supervise the bridge's structure deformation, seismic and thermal stress can also be profited to monitor the bridge traffic, or the weather and pollution conditions. Consequently, in order to achieve energy-efficient sensor networks, the networking protocols need to allow different modes of operation and adapt to the likely changing network conditions. Moreover, these operational changes should be performed automatically without the need of manually reconfiguring the entire network.

The purpose of listing the various WSN applications and analysing their diverse functional requirements has been to identify the challenges for hardware and software design that appear on such variety of sensor deployments. This provides the motivation for the research reported in this dissertation.

1.3 Features and Non-Functional Requirements

In view of the diversity of applications, sensor networks need to offer different non-functional requirements (properties the network must exhibit). Despite such a variety of applications, the following requirements are universal in WSNs: low cost, low power consumption, self-configuring and wireless network connectivity. In addition, a minimum latency and a time synchronisation method are commonly required in WSNs. These attributes are very interrelated in these networks and the pursuit of optimal designs is more difficult. Often it may be necessary to decrease performance in one metric, such as sample rate, in order to increase another, such as lifetime. For a given application, the hardware and software can be designed to fit their specific requirements. Conversely, and commonly in real situations, for a given WSN platform (hardware and software architecture), the protocols and parameters must be tuned to achieve these requirements and to effectively profit from the platform capabilities.

This thesis concentrates in radio communications related non-functional requirements. This section describes the most important requirements of the communications network and how those translate into explicit node's requirements of the radio hardware and protocols.

1.3.1 Lifetime and low-power operation

Maximisation of the network lifetime is always desired in sensor networks. In the majority of applications scenarios the nodes have to be self-powered and last for years. This demands the average energy consumption of the nodes to be as low as possible.

An ultra-low-power operation is only possible by combining both low-power hardware components and low duty-cycle operation techniques. Thus the goal is to minimise both the time that an operation takes and the current consumed during that operation. The prime power saving in sensor networks actually comes from the power management (PM).

Consequently, the microcontroller must be able to turn on and off the sensors and peripherals, and affect the radio duty cycle as well as its own operation. Among these devices, the most significant factor in determining lifetime of a given energy supply is the radio power consumption [26]. The radio device is managed by the medium access control (MAC) that is also responsible for sharing the limited communication resources fairly and efficiently between the nodes. Because the constraints on energy resources, storage and computational ability, MAC design in sensor networks needs to be very different from the traditional wireless networks. As a result, algorithms and protocols must be developed to reduce radio activity with more efficient access control, which may include diverse access techniques such as contention [27], polling [28], scheduled [29] or hybrid [30] MACs.

Furthermore, in nodes-to-sinks applications, it is not the average node lifetime that is important, but rather the minimum node lifetime. The most energy-vulnerable nodes are in general chief participants in the communication process. Thus, extension of the network operational lifetime lies in the ability to postpone battery depletion of these critical nodes.

1.3.2 Coverage, radio transceiver and antenna design

Next to lifetime, coverage is a key attribute in sensor networks. In many applications it is advantageous to extend the physical area of the deployment. However, the transmission range has a significant impact on the minimal acceptable node density. With nodes located too far apart it may not be possible to create an interconnected network or one with enough redundancy to maintain a high level of reliability.

On the other hand, for a given sensor network deployment, the available range decides on the minimum number of communications hops required to link the network. In addition, the feasible transmission distance can vary with the tuning of the power transmission, a common ability of radio devices used in WSNs. Pursuing more energy-efficient wireless communications [31], tradeoffs must be considered in the range selection with regards to the impact of multi-hop communications. In the energy analysis presented in [32] it is shown that fewer hops communications lead to more energy-efficient networks; the condition being that the maximum link distance has moderate path loss (i.e. considerable margin over the sensitivity level). With more nodes sharing the medium access for transmissions the use of fewer hops is shown to be more energy-efficient [32]. However multi-hop may be favoured with respect to the single-hop distance if the path loss exponent is greater than 3, for example.

Depending on the application and deployment scenario (indoor, outdoor), the required range can drastically differ in WSNs. The selection of the radio device, thus the available frequencies and power levels, in addition to the antenna choice determines the available ranges. Moreover there is already a wide range of available transceivers in diverse ISM bands manufactured to be used in sensor networks. There are many possibilities, from long range of kilometres [33] (>10km) necessary to monitor temperature and salinity on the Great Barrier Reef using Mica 2 [34] mote in the 40MHz band and a long whip antenna; to centimetric ranges [35] (<1m) for densely-packed WSN deployments, such as smart home environments, with the use of tiny nodes (e.g. future specknets [36]) in the 2.4GHz band and small printed antennas.

Particularly, the antenna design in WSN is both important and difficult because of the low cost and size requirements. This situation often results in the need to adjust the antenna design to fit the aesthetics of the sensor node's physical design [37]. As a result low efficiency antenna systems are being designed in WSN platforms and higher transmission power is used to obtain the required effective gain. One possible solution is to profit from the higher gain of directional antennas to achieve the required network connectivity with smaller transmission power.

Additionally the required range, and thus the radio transceiver choice, usually delimits the available communications data rate. Higher communication rates translate into the ability to achieve higher effective sampling rates and lower network power consumption. As bit rates increase, transmissions take less time and therefore potentially require less energy. However, an increase in radio bit rate is often accompanied by an increase in radio power consumption. Certainly, design and selection of the radio hardware is critical in WSNs.

1.3.3 Self-Configuration and Adaptability

A wireless sensor network must be able to configure itself, at the beginning of the network life and whenever the user requirements or network conditions change. The communication protocol needs to be capable of performing link discovery to establish the routing paths. The radio device should support these routing decisions with an indication of the link quality and signal strength.

In addition, WSNs should provide means of adapting to cope with post-deployment changes. During network operation, environmental conditions, radio interferences, obstructing objects, node failures or relocation may interrupt the communication link between two nodes. The network should be able to detect and automatically adapt to these occurrences. In some applications, e.g. a security system for fire alarm or intruder detection, nodes must be also allowed to request external maintenance if required.

1.3.4 Latency and Time Synchronisation

The ability to offer low latency of the generated sensing data conflicts with most of the techniques used to increase network lifetime. There are two critical application design parameters, how often sensor readings are made (the effective sample rate) and the length of the intervals on which these readings are communicated to the collection points (the frame duration). Many monitoring and data-collection applications do not demand high sampling rates, and sensor readings can take place every few seconds or minutes; thus very low duty-cycles can be assumed. However, in addition to the sample rate of each sensor, it is important to consider the ability to effectively relay the data of surrounding nodes when the impact of the multi-hop networking is significant.

The nodes can exploit aggregation of data [38] or in-network processing, such as spatial and temporal compression [39], in order to reduce the amount of data that must be forwarded. In any case, Routing and MAC protocols must be designed to efficiently carry multi-hop communications with a more equitable sharing of radio resources to reduce congestion problems.

In order to support time correlated sensor readings and low-duty cycle operation a global reference clock is maintained on each node throughout the network [40]. Precise time synchronisation requires first, the use of higher accuracy clock systems [41], and second, an effective mechanism to distribute and maintain network timing and compensate for clock inaccuracies [40]. Some synchronisation techniques require extra signalling [27][42] and, if frequently performed, may involve significant extra energy usage. On the other hand, in contrast to TDMA-based access protocols (e.g. LEACH [29]) or scheduled contention access (e.g. S-MAC [27]), the use of a pseudo-asynchronous rendezvous MAC (e.g. B-MAC [28]) for duty-cycle control avoids the need of a global time reference.

1.4 WSN Constraints: Energy Wastage and Link/Node Failure

1.4.1 Energy Wastage in the Radio Communications

With provision of an ultra-low power sleep mode at the sensor nodes, if the sensors and microcontroller are operating correctly, the main reasons for the wastage of energy appear within the radio communications. With the assumption that WSNs have a common frequency channel and shared time for communications, it is possible to identify five main contention problems that involve energy wastage: collisions, idle listening, overhearing, over-emitting and control packet overhead.

1. *Collisions* appear when a receiver node receives more than one packet at the same time. *Collisions* force packets to be discarded and retransmitted, which increases the energy consumption.
2. *Idle listening* occurs when nodes are listening to an idle channel to receive possible traffic. The receiving state is typically one of the most power-hungry operations in the 'low-power' transceivers being used in WSNs (e.g. the CC2420 [43]). Consequently *idle listening* is one of the main reasons of energy waste in CSMA-like MACs, such as S-MAC [27], and mechanisms such as an adaptive duty-cycle [44] are being proposed to reduce the active time of the Radio.
3. Related with *idle listening*, is *overhearing* (i.e. receiving) packets that were destined for other nodes.
4. *Over-emitting* is caused by the transmission of a packet when the destination node is not ready.
5. The last reason of energy wastage comes as a result of control packet overhead in the signalling process of the contention mechanism, routing or synchronisation scheme. Control packets are needed, but as far as possible their use should be minimised in WSNs.

The extent of these problems depends on the level of network congestion that is caused by the intensity of traffic (in the wake period of the duty cycle) and the effectiveness of the MAC for sharing the limited communication resources. In addition, the impact of congestion thorough the network varies because of the non-uniformity of traffic inside sensor networks [45]. In nodes-to-sink applications, the funnelling effect [46] results when periodic reports or alarms are generated and then move through the network on a hop-by-hop basis toward the sink. The funnelling effect leads to a number of significant challenges including congestion, packet loss, and therefore wasted energy and bandwidth. As a result the sensors nearest the sink will use energy at the fastest rate, having a significant impact on the operational lifetime of the network [45].

1.4.2 Radio Link and Node Failures

In addition to the collisions, the particular propagation characteristics of low-power WSN radio signals is a determinant cause of unpredicted packet losses [47]. Several empirical studies have demonstrated that sensor networks of the lowest power radio devices exhibit complex behaviours not easily captured by simple propagation models. For example, the reception of packets over distance reveals a large and highly variable "gray area" [48]; receivers located at distances inside this gray area are likely to experience unreliable packet reception. In [49] it is demonstrated that node-pair transmissions have asymmetric loss rates. Findings from these experimental studies serve to establish important considerations and guide the design of sensor network protocols. For instance routing decisions should take into account the unpredictable channel behaviour with the selection of 'stronger' links more resilient to the variability of the signal strength.

Furthermore, wireless sensor networks are inherently fault prone and vulnerable mainly due to battery depletion, reconfiguration events (node addition and deletion), link failure and congestion [50]. Such failures are more likely in sensor networks than in traditional distributed systems due to the unpredictable operation environment. Fault (or failure) management is therefore essential to maintain the healthy operation of a WSN. It has been suggested that in dense sensor networks, the natural redundancy of large numbers of nodes or data correlation techniques [51] in time and space can absorb the problems derived from node or link failures. In [52] for example, to compensate for the funnelling effect in a single sink network, it is proposed to place a larger number of nodes (backup nodes) near the sink.

However the benefits of such network redundancy are not always possible or affordable, for example in randomly deployed networks, and can be inappropriate to guarantee a resilient operation in WSNs if the addition of more nodes incurs higher amount of congestion problems. In any case, node failures at earlier times than expected derived from the non-uniformity of battery depletion should be tackled, firstly, with more efficient Routing and MAC protocols, and secondly, with failure management schemes directed to postpone the demise of energy-vulnerable nodes.

1.5 Research Context: DIAS Project

The research work of this thesis has been developed within the DIAS-MC project [2]: Design, Implementation and Adaptation of Sensor Networks through Multi-dimensional Co-design. DIAS is a collaborative project that combines the expert competencies of five institutions and is funded under the EPSRC WINES Programme. The overall goal of the project is to develop methods and tools for the design, implementation, and adaptation of entire environmental sensor network systems. The hypothesis is that by simultaneously considering the system requirements for each of the primary design dimensions of an environmental sensor network, and armed with the expression of a global cost function for the system, co-design techniques can be used to generate heuristically optimal designs.

1.5.1 Motivation and Objectives

DIAS focuses on sensor networks that consist of small, battery-powered, wireless sensors that may be tethered or mobile. For such systems, it is needed to minimise power consumption while delivering full functionality.

With increasingly flexible hardware structures in embedded systems, there is particular interest in the "optimal" partitioning of functionality across the hardware/software boundary; this approach to optimising HW/SW issues in tandem is termed "co-design". HW/SW co-design is a hot topic in the embedded systems community, especially for sensor nodes [53][54][55]. Co-design is a methodology that integrates orthogonal design methods; the goal of co-design is that the integrated design will better meet system requirements than the sum of the orthogonal designs.

One of the primary challenges in the design of effective sensing systems is the sheer number of dimensions (also termed “areas of concern”) that must be jointly considered and seamlessly integrated. The major dimensions of sensor systems in DIAS [2] are: application, monitoring and control, communication network, and operating system. For WSN, the network dimension is further subdivided into communication protocols and radio capabilities.

So far, the practice has been to address each of these dimensions orthogonally (independently), with the result that any potential synergies available through co-design are not achieved. DIAS intends to use co-design to integrate the design of the hardware system and all dimensions of the software system, across the HW/SW boundary.

The overall objective of the project is to employ generative programming techniques to construct sensor systems that are optimal with respect to a chosen, global cost function, formally validated with respect to required system properties, and adaptive to changing conditions in the field. The end result should be the ability to design, implement, deploy, and adapt sensor systems that are optimised to minimise a much more complex and realistic combined cost function. This goal requires investigation in a number of research areas: Radio Communications, Networking and Operating Systems, Network Management and Monitoring, Application Data Management, Formalisation and Generative Programming and Adaptation.

1.5.2 Approach

DIAS proposes to enable a designer to specify the requirements for a particular sensor system in each area of concern orthogonally, and to then use co-design tools to produce integrated designs and implementations that achieve substantial synergy and better reflect the underlying physical environment of the sensed system. This generation phase is optimised with respect to a combined cost function for the target system. Iterative specification/integration will most likely be required to maximise synergy. The end solution should combine a pre-deployment and a post-deployment architecture. Design of the **Pre-Deployment Architecture** has the next steps:

1. An end-user, such as a scientist or an engineer, specifies the desired WSN requirements, in terms of Functional and Non-Functional requirements. Non-Functional Requirements will relate to Quality of Service (QoS), such as lifetime, latency, data acquisition frequency, etc
2. Given these requirements, and supported by a previous study of the interdependencies and trade-offs of different design parameters, a series of cost functions are established.
3. Attending to these cost functions, the DIAS 'tool' will select appropriate hardware and software components from the Library (set of available parameterised solutions) in order to satisfy the user specifications.
4. The proposed HW/SW design is verified and implemented.

An objective of DIAS is to produce sensor networks which are adaptive post-deployment, and are therefore heuristically optimal at all times. The WSN should adapt to changing conditions in the field, the loss of nodes, or changes in the application requirements. The design of a **Post-Deployment Architecture** consists of:

5. A Network Management entity to monitor the performance of the deployment against the user's original QoS requirements.
6. Co-design techniques to detect network dynamics, such as node failures.
7. A set of HW/SW solutions to confront the violation of the QoS requirements. While most of the HW/SW configuration aspects cannot be changed at deployment time, some radio communications solutions, in particular, are able to adapt its operations. These include adaptive Routing-MAC protocols, Radio power control and the use of directional antennas.

1.6 Thesis Research

Inside the DIAS context, the research work undertaken by the Strathclyde team concentrated on the network communications dimension. The research in this thesis has focused on the design of energy-efficient and adaptive communications protocols that explore and make use of new techniques in WSNs including hybrid radio access control, proactive failure management and directional "smart" antennas. The solutions proposed are the result of a co-design process inside of a cross-layer architecture that allows for understanding interactions between components and benefits the hardware capabilities more efficiently to achieve the applications requirements.

1.6.1 Motivation

In view of the future applications for WSNs there is a high expectation of the capacities that the sensor nodes, and principally the whole network system, should exhibit to achieve the stringent functional and non-functional requirements; a main concern being the high number of nodes and long lifetime expectancy. However major difficulties appear in the design of efficient communications systems in today's sensor networks due to the inherent deployment conditions and technological limitations. In particular the main challenges that can be identified from the exposition provided in this chapter are:

- Application trends to consider the deployment of hundreds of nodes that need to autonomously configure to form interconnected operational networks.
- With a limited range, a fully connected network requires the use of multi-hop communications that require a radio sharing access mechanism.
- The energy consumption of the radio device in sensor nodes has the major impact on battery depletion. A necessary low-power operation forces the radio device to remain asleep as much as possible.
- With an increasing number of nodes, multi-hop traffic and limited radio access time; nodes need to compete to access the channel and congestion problems appear.
- In common data-centric applications, traffic confluences occur in one or few gateway nodes (sinks) and cause a funnelling effect that decreases network efficiency.
- The non-uniformity of traffic and congestion thorough the network increases the unfairness in energy consumption which promotes energy-vulnerable nodes.

- Network dynamics such as variable traffic conditions, radio link interruptions or node failures are likely to appear and need to be detected and accommodated.

Consequently radio communications design in WSNs is focussed on achieving the application requirements while using minimal energy. New Routing-MAC techniques in sensor networks must be co-designed with consideration of the radio HW capabilities and limitations, minimising energy wastage and being adaptive to changing conditions on the field.

1.6.2 List of Assumptions

The design and assessment of the communications solutions proposed in this thesis have considered several assumptions of the type of applications and scenarios targeted, as well as of the nodes hardware and basic functionality required. The main assumptions are:

- Multi-hop nodes-to-sink(s) applications with one or more sinks that initiate and control the network operation, and serve as collection points of the data packets generated at the sources. The sink is regarded as a special node designed to collect data in a specified form and to forward that data to a higher level network component for subsequent processing. Normally only one sink (located at the centre of the network area) will be considered; although in some scenarios evaluated in this thesis more than one sink will be deployed.
- Monitoring applications with periodic traffic which data rate can change during the network operation. The frequency of the generated sensing data can differ significantly in different applications and this thesis considers a range of data rates (from 1 to 0.0025 packets per second) that have been used in other related works. In addition, the communications system should be designed to handle time-critical data (alarms).
- Outdoor environments where nodes are stationary and within line of sight. However the static network needs to support the incorporation of new nodes at any time after the initial deployment.

- Relatively large networks in size (areas between 500m by 500m to areas of 1000m by 1000m) and number of nodes deployed (between 50 to 600 nodes). Therefore different network densities can be considered with the condition that any node has at least one neighbour that can route the packets towards one of the sinks.
- Nodes in the network share the same frequency channel and have common channel access time for detection, transmission and reception of sensing events and network information. Hence a base contention MAC is required for the multi-hop forwarding process in the nodes-to-sink monitoring applications.
- The network is composed of homogeneous nodes in terms of SW protocols and HW (the HW platform Tmote [88] has been considered). However the adaptive communications solutions in this thesis attain a heterogeneous post-deployment operation of each individual node and of set of nodes (e.g. one-hop nodes) with regards to the actual network conditions. In addition the sink can mount different type of antennas and its battery level in any scenario is big enough to ensure that the sink will be the last node to die.

1.6.3 Research Questions

During the research process several questions have arisen. These questions have motivated the methodology and solutions proposed in this thesis. The main ones are:

1. Which method should be used to integrate the design of Routing and MAC protocols with respect to the application requirements and interactions with the physical layer?
2. How can a communication system be modelled and evaluated to reveal the dependency of the overall power consumption on the design parameters of the network?
3. What kind of self-configuration and routing mechanisms are necessary in WSNs, and how can these be designed to incur minimum energy overhead for its maintenance?

4. Which MAC techniques can be implemented to reduce problems derived from congestion and the funnelling effect while minimising the time needed for communications?
5. How may directional antennas be combined with these MACs to profit the directional capabilities and further reduce congestion problems?
6. What solutions can be adopted to be resilient to dynamic changes in network condition. In particular, how can the network circumvent failures from energy-vulnerable nodes?

1.6.4 Organisation of the Thesis

The rest of the thesis is organised as follows: Chapter 2 covers the state of the art in WSN research of communications solutions. Chapter 3 introduces the co-design of the cross-layer adaptive developments proposed in this thesis and describes the methodology used for the co-design and assessment. The evaluation environment within a flexible cross-layer communications architecture (XLCA) is presented in Chapter 4 which explains the requirements of functionality and the modelling of the elements needed for performance evaluation. Chapters Chapter 5 Chapter 6 and Chapter 7 explain and evaluate the cross-layer solutions that have been co-designed inside the XLCA. In Chapter 5 , the directional contention MAC (*Dir*C-MAC) is proposed to reduce congestion problems in WSNs with the incorporation of directional switched beam antennas. A sink-oriented localised hybrid MAC (SSAS) is presented in Chapter 6 to reduce the funnelling effect and increase network adaptation capabilities. In Chapter 7 , multi-layer proactive schemes to postpone failures of energy-vulnerable nodes are described and compared using SSAS as based communication protocol. A discussion summary of the results is included in Chapter 8 . Chapter 9 concludes the thesis.

1.7 Objectives

The main objectives that this thesis addresses are:

1. Provision of a framework for the Co-Design and evaluation of new energy-efficient communications protocols.

2. Increase the ability to reduce congestion problems derived from the contention access and minimise energy waste of radio resources.
3. Mitigate the negative impact of the funnelling effect close to the sinks in data-centric nodes-to-sinks applications.
4. Offer adaptability skills to confront network dynamics and adjust the nodes operation to optimise energy usage.
5. Extend the lifetime of the most energy-vulnerable nodes.

The ultimate goal is to maximise the operational network lifetime on which the established application requirements are preserved.

1.8 Contributions

The main contributions that will be described in this thesis are summarised next:

- A cross-layer communications architecture (XLCA) that is modelled and implemented inside a simulation framework exercised for the co-design and assessment of cross-layer techniques in WSNs.
- The design of adaptive MAC mechanisms to optimise the use of the nodes resources and to adapt the nodes operation in the event of network dynamics.
- The introduction of switched beam directional antennas with co-designed contention MAC schemes that effectively reduce congestion problems in the entire network.
- The development of a sink localised hybrid MAC that achieves a high reduction of the congestion problems derived from the funnelling effect and, as a result, significantly improves the capacity and longevity of the network.
- The devise of cross-layer Routing-MAC-PHY proactive schemes that are autonomously triggered at the most energy-vulnerable nodes, accomplishing an extension of the operational lifetime of these nodes, but also of the entire network longevity.

The cross-layer developments presented in this thesis have led to a series of publications that are listed in Appendix B: Papers Published from this Work.

Chapter 2

State of the Art in WSN Communications Design

In the last few years there has been an explosion of research and proposals in the field of wireless sensor networks. This chapter presents some of the significant contributions which relate with the solutions that have been investigated in this thesis. The state of the art reviews five differentiated research areas in WSNs:

- cross-layer frameworks,
- self-organising and routing mechanisms,
- energy-efficient MAC protocols,
- use of directional antennas and,
- failure management mechanisms.

2.1 Cross-Layer Design Frameworks

The heterogeneous WSN in terms of applications requirements, communication protocols and hardware characteristics is demanding cross-layer designs that can merge more efficiently such a diversity of solutions. Cross-layer design consists of removing the traditional layered architecture of the networks and providing more flexibility to the designer. Layers interact by sharing information and feedback, thus adaptation to changing conditions is enhanced. For example, minimising the energy consumption is likely to require interactions between the radio operations, the access control on the channel and the routing protocol. A routing protocol that can use congestion information from the MAC layer to carry out the path calculation can help reducing unnecessary re-transmissions and thus result in a decrease in energy consumption.

Cross-layer optimisation is starting to be widely used in the context of designing wireless networks for low power nodes. Indeed, because of memory and battery capacity constraints, the traditional layered architecture is viewed as being too inflexible for minimising code size and cooperation or for feedback between layers to report current network conditions. The work presented in [56] proposes an optimisation agent that can provide information either top down or bottom up so that the layers can benefit from current network conditions. Alternatively, a specific service (e.g. Information Exchange Service (IES) proposed in [57]) may be employed in order to maintain useful information from all layers and accessible by any layer, thus enabling cross-layer optimisation as well as providing the application's requirements to other layers.

A few cross layer architectures such as X-lisa[58], TinyCubus[59] or SensorNet[60] have been proposed. These mostly consist of implementing sharing of information between layers and enabling interactions between components.

X-lisa [58] introduces a Cross-Layer Optimization Interface (CLOI) that facilitates horizontal and vertical cross-layer information-sharing. The CLOI keeps updated information on the network state, the states of the nodes and the messages to be sent.

The architecture TinyCubus [59], in support of cross-layer information exchange, offers a configuration engine that allows code to be distributed reliably and efficiently by taking into account the topology of sensors and their assigned functionality.

The Sensornet Protocol (SP) [60] provides a unifying cross-layer abstraction designed to be capable of running over a broad range of link-layer technologies and supporting a wide variety of network protocols. The SP has been implemented effectively in TinyOS [61] on top of two very different radio technologies and MACs: B-MAC [28] on Mica2 [34] and IEEE 802.15.4 [62] on TelosB [63]. Ultimately, the goal of the SP architecture is the evolution towards a full protocol definition with communications services and interfaces, similar to IP.

It is of particular interest for this thesis the advantages of using cross-layer architectures and the proven efficiency of cross-layer design in various sensor networks aspects. Cross-layer is seen as an effective tool for co-design SW and HW in WSNs that is a main concern of DIAS and particularly of this research for the design of energy-efficient and adaptive communications.

2.2 Multi-Hop Self-Organising and Routing Mechanisms

The literature provides numerous multi-hop ad-hoc routing mechanisms, where configuration of nodes, neighbour and routing discovery is carried out through a self-organising initialisation phase [64][65]. Once the routes along the whole network have been established, the configuration process ends, and a maintenance routing procedure preserves and refresh these routes. Regarding the target application, these mechanisms can be organised in three categories [64]: *tree-based*, where nodes send or relay data towards one or few base stations, *intra-network routing* that assumes peer-to-peer in-network data exchange, and *dissemination routing*, where data is broadcast to entire regions. In monitoring applications tree-based collection is principally used, whereas intra-network routing can be useful for self-decision applications that include actuator nodes; e.g. after detection of low soil moisture a sensor node generates an alarm event that is routed to the actuator node that opens the drip irrigation. Dissemination (flooding) is broadly used to reconfigure or send commands, such as applications requirements, from the control nodes (sinks) to the entire network.

The route discovery process can be either destination-initiated (pull) or source-initiated (push). Furthermore, routing algorithms in WSNs can be further classified in sub-categories [65] with regards to the network structure (flat based, hierarchical or location based) or with respect to the protocol operation (negotiation, multi-path, query or QoS based routings). Among the pool of WSN routing protocols, this thesis concentrates on those that construct routing trees in nodes-to-sink applications. Some interesting ones are:

Directed Diffusion (DD) [66][67] is a data-centric query-based pull routing mechanism in which the destination (sink) sends interests that are flooded over the network in order to select sources nodes, the ones that can offer the requested data. During the interest broadcast, nodes set gradients that are used to select the 'best' next-hop neighbour from the multiple paths in which copies of the interest packet have arrived. Therefore, the dissemination process serves to establish routing trees from sources towards the destinations. However the use of plain flooding as forwarding technique may be inadequate in dense multi-hop WSN.

Energy Aware Routing (EAR) [68] is a multi-path tree based protocol that, contrary to DD, maintains a set of paths instead of maintaining or reinforcing one optimal path. The path selection depends on a certain probability calculated with respect to energy costs of each path. In EAR, like in DD, localised flooding is performed by the destination node to refresh the paths.

Energy-Aware Virtual Backbone Tree (EVBT) [69] is a tree based routing protocol which is focussed on a cost function called *fitness indicator* that considers length and direction of the links as well as the nodes energy level, the EVBT selects paths with high energy levels. To further distribute the energy dissipation, the paths are periodically re-constructed and the sink can move to alleviate the consequences from the funnelling effect. In addition the algorithm adjusts the radio transmission power to each link range.

Low Energy Adaptive Clustering Hierarchy (LEACH) [29] is a cluster-based hierarchical routing protocol with distributed cluster formation. The algorithm randomly selects cluster heads (CHs) and rotates the role to distribute the energy consumption. The traffic flow goes from nodes to the CHs and from CHs to the sink. Intra-cluster data communications use Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) is implemented for inter-cluster interference avoidance. The use of LEACH in real applications may be restricted due to scalability constraints and radio hardware requirements to perform CDMA.

Despite the different strategies of these and many other routing protocols in WSNs, such protocols are commonly designed for data-centric applications with a general purpose of reducing energy consumption. Data-centric implies that the data itself is more important in the network than the sensor nodes that have sent it. This is an important consideration in sensor networks that permits the reduction of the design complexity of the routing layer, with a consequent decrease of energy overhead in the routing formation and maintenance. For this purpose it is promising the integration of Routing and MAC with the use of cross-layer information exchange.

Although routing is not the central focus of this work it is a key element in the Co-Design of communications solutions. In particular, routing has important relevance within this thesis in the design of adaptive MACs and the deployment of switched beam antennas.

2.3 MAC protocols

Numerous MAC protocols have been developed in recent years within the WSN research activity [70]. Since radio communications account for the major energy consumption, energy management at the medium access control (MAC) is essential. S-MAC [27] revolutionarily introduces duty cycles, periodically putting active nodes into sleep (with radio turned off) to save energy. Among the different MACs in sensor networks, power management strategies to maximise the radio sleep time are always present. Typically three different channel access mechanisms are considered: scheduled contention, channel polling and time division multiple access.

In the first category, protocols such S-MAC [27] or T-MAC [44] periodically wake up nodes in unison contending to access the channel in an IEEE 802.11 manner and after going back to sleep. In S-MAC the nodes must be deployed with an active time that can handle the highest expected load. Whenever the load is lower than that, the active time is not optimally used and energy will be wasted on idle listening. T-MAC improves S-MAC's energy usage by introducing adaptive duty cycle. In both, the wake/sleep scheme requires synchronisation among neighbouring nodes. In order to prevent long-time clock drift the neighbouring nodes need to periodically update each other with their schedules. Moreover, a main limitation of scheduled contention protocols is the impact of congestion problems, such as those presented in Section 1.4, which are intrinsic due to the shared channel access and more significant with higher number of nodes.

Polling channel protocols like B-MAC [28] assume a low power listening (LPL) scheme where nodes independently wake up to sample the radio channel for activity, turning on the radio, if busy, in order to receive a packet. The transmitter nodes send a preamble before the data packets long enough to allow a prompt detection of the ongoing transmission at the receivers that intermittently sense the channel. B-MAC is an energy efficient protocol for event detection applications, and provides low latency delivery at the sink, which makes it attractive for transmitting alarm packets for example. However the use of long preambles as lack of overhearing avoidance limits its performance in nodes-to-sink applications with periodic traffic and large deployments.

TDMA protocols like the GTS portion of 802.15.4 [62] and LEACH [29] divide time into slots and allocate these slots to all nodes in a neighbourhood, usually organising nodes into cluster hierarchies. Despite providing collision-free access, limited scalability and complex requirements such as tight synchronisation or clustering formation overhead, reduce the attractiveness of TDMA proposals for many WSNs applications.

In view of the advantages and disadvantages of each of these protocols, the most appropriate choice will vary depending on the characteristics of the application considered. The intention of this thesis is to choose a protocol that covers a broader range of applications and also provides the ability to adapt to changes in the network.

2.3.1 Hybrid MACs

Tradeoffs among the previous three MAC approaches have motivated the creation of hybrid protocols. SCP [71] combines scheduled contention and channel polling by synchronising wake up times to sample the radio channel. Two other protocols, Z-MAC [72] and Funneling-MAC [30], combine CSMA (based on B-MAC) and TDMA access control. In both schemes the TDMA approach is triggered when the traffic conditions exceed a defined threshold although the extent of nodes that swap the access mode is different.

Z-MAC employs a TDMA-style slot allocation for all nodes in the network under high traffic conditions, but allows accessing other nodes' slots using channel polling and CSMA with low traffic. However, Z-MAC is not designed to alleviate congestion problems and the funnelling effect from higher traffic closer to the sinks and also, it entails high overhead due to the complexity of the scheduling DRAND algorithm [73].

Alternatively, the sink-oriented Funneling-MAC is designed to mitigate congestion closer to the sinks, using TDMA scheduling for aggregated paths among neighbours inside the range of the sink, which are assumed to use lower transmission power than the sink. The depth (number of hops) of the intensity region (scheduled access) adapts to the traffic load. Although the TDMA access is only used locally, the Funneling-MAC in [30] outperforms Z-MAC under various network conditions. The authors in [30] concluded that when the network is saturated the optimal path depth is of 1-hop, meaning that only the direct neighbours of the sinks use TDMA for transmitting their packets. This is an important consideration that suggests the advantage of increasing the number of nodes that access directly to the sink, with the use of directional antennas for example, if hybrid access techniques come into action.

2.4 Directional Antennas in WSN

Although the directional antenna concept is a well-known technology with proven effectiveness, its use in sensor networks has been limited to date. Santivanez and Redi [74] address significant issues for contention–based MACs using directional antennas, which are of particular interest to sensor systems. They also propose a MAC based on DMAC although no results are shown. Work in [75] presents a routing protocol for WSNs that takes advantage of directional antennas to reduce network delay. Researches in [76] show network life improvements of a protocol that uses a directional antenna mounted only at the sink. The target of the protocol is to increase the number of nodes that can directly access the sink in order to reduce the amount of multi-hop transmissions and spread the traffic load, and thus the energy consumption, among a higher number of sink's neighbours. However, very simplistic antenna and radio models are assumed and the mechanism for collision avoidance at the nodes neighbouring the sink is not described.

In addition to the proposed protocols, some experimental works have focused on the actual implementation of sensor nodes with directional antennas. Authors in [77] have designed an assembled a sensor platform with a simple two wire antenna switched beam array that is capable of producing two diverse beams oriented towards opposite angles. In [78] a four-beam patch antenna (FBPA) is mounted in an IEEE 802.15.4 radio showing range extension and interference suppression of IEEE 802.11 signals.

Despite the scant regard of directional antennas in sensor networks, their capabilities are very attractive to tackle various challenges in WSN design. These include the ability to reduce congestion problems discriminating the direction of transmission, or increase the range with a higher antenna gain. Technological advances are enabling the development of small (~5cm) switched beam antennas [79] that could be included in WSNs, not necessarily on all nodes, to take advantage of these capabilities.

2.5 Failure Management

As stated in Section 1.4, the limited resources and capabilities of nodes, together with stringent operation and deployment conditions, precipitate the occurrence of node failures in WSN. Generally, failure-tolerant schemes can be classified into two categories: reactive or proactive. A reactive scheme is designed to react to a failure that has occurred and to recover from that failure, whilst a proactive one attempts to detect a potential failure in advance and to "prevent" (or actually postpone) it. Typically, the proactive approach is more attractive since failure prevention tends to be more effective in avoiding performance deterioration. Nevertheless, a proactive scheme usually demands more intelligence and could incur more overheads. Despite the differences, both approaches would normally need well-defined metrics to identify the failure and then trigger the corresponding recovery or prevention procedure.

Battery depletion is the most common cause for node failures in energy-constrained WSNs [80][81]. Conventionally, the *Residual Battery* metric is used to monitor energy consumption. However, the values of this metric have little meaning unless they can be collected and compared with each other. This indicates that global knowledge of all nodes' information is typically required for the post-analysis, which is undesired especially in large-scale WSNs due to the considerable processing and signalling overheads. For example, the eScan scheme [80] requires each node to monitor its residual battery and periodically report to the sink so that a global energy map can be produced. In [81], thresholds are set to reduce the signalling frequency although each node is still required to report to the sink.

Typical techniques for failure recovery consist of routing decisions. Reactive rerouting schemes [82], diversion of the traffic to alternatives routes, if possible, after failure detection. Unfortunately, rerouting can degrade the overall network performance by deteriorating alternative routes with additional congestion. The more attractive, yet challenging, approach is to proactively detect potential failures and adapt the network communications to prevent or postpone the failure. Consequently, the network usability can be extended. Previous power-aware dynamic routing algorithms such as [83][84] typically employ (normalised) *Residual Battery* as the metric when choosing the next-hop node. A sender needs to know the up-to-date battery state of all the next-hop nodes to make a routing decision. Alternatively, periodic reconstruction of paths in energy aware routing algorithms, such as the EVBT [69], intrinsically involve prevention of energy-vulnerable nodes, at the cost of reconstruction, but without the need of spreading *Residual Battery* levels.

Within this research, the implementation of mechanisms for failure management is considered vital to extending the operational life in sensor networks. However, the 'remedy' should not be worse than the 'disease', and therefore the mechanisms for detecting and recovering from failures should be efficient in themselves from the energy perspective.

2.6 Design Guidance from the State of the Art

This chapter has presented different design guidelines in several communication related aspects. Interesting remarks that have guided design decisions on this thesis are:

- Cross-layer architectures appear to be a promising method to combine techniques from different layers and to co-design SW/HW more efficiently.
- Routing mechanisms can distribute more evenly energy consumption in the network. However routing maintenance in dense multi-hop WSNs using

periodic broadcast of routing packets may incur significant overhead. In addition routing protocols do not reduce the congestion problems caused by the funnelling effect in nodes-to-sink applications.

- The need of scalable and adaptive sensor networks requires a sharing time for negotiation; this conforms to the skills offered in scheduled contention MACs. In order to alleviate congestion problems and the funnelling effect, hybrid MAC techniques can locally be applied without compromise adaptability.
- The necessary use of MAC control packets can be profited by upper layers to share routing information, maintain synchronisation or spread application queries and commands.
- Commonly, proactive failure management focuses on dynamic routing algorithms to curb battery depletion in energy-vulnerable nodes. However, these nodes are usually located in hot-spots where, in fact, adaptive MAC techniques can have a greater impact on reducing the congestion and energy consumption problems that increase nodes vulnerability in those regions with high traffic intensity. Moreover MAC decisions do not involve routing changes and thus avoid the problems of transfer traffic load to alternative routes.
- WSNs can take advantage of directional antennas and their capabilities of higher gain and directional spatial diversity.

From the point of view of this thesis, most of the above proposed techniques have been minimally investigated in wireless sensor networks. Their inclusion in future communications systems can offer substantial benefits.

Chapter 3

Co-Design of Communications in Wireless Sensor Networks

Chapter 1 has described application and design requirements in WSNs as well as the need for adaptability and important constraints in the communications design. Subsequently Chapter 2 has depicted significant strategies for the design of communication protocols in sensor networks, and Section 2.6 highlighted that, in spite of the important advances, WSN applications still pose significant challenges. Bearing in mind the motivation, questions and objectives of this thesis exposed in Chapter 1, and referring to the findings identified in Chapter 2, this chapter focuses on describing the co-design of cross-layer adaptive communication solutions in this research. The broad Co-Design objective is to achieve full network functionality (in terms of application requirements) whilst minimising the total power consumption and offering adaptive solutions to accommodate network dynamics.

The work described in this thesis was undertaken as a contribution to an EPSRC funded programme known as Design, Implementation and Adaptation of Sensor Networks through Multi-Dimensional Co-Design (DIAS-MC). There were several aspects to this programme, one of which was to define and integrate the communications aspects of co-design into the overall co-design concept. The underlying theme of the communications developments was the definition and integration of adaptive systems into the overall co-design philosophy of the project. This thesis concentrates on a sub set of the co-design issues emanating from the incorporation of adaptive wireless communications procedures. In particular the adaptive communications aspects incorporate several cross layer optimisation techniques which cover routing, adaptive MAC design and the integration of smart antenna technology. These aspects of co-design are part of the overall co-design philosophy of the project. In order to indicate the context of the demands on the communications co-deign aspects a brief summary of the general co-design objectives is presented next.

The proposal of DIAS-MC was to enable a designer to specify the requirements for a particular sensor system in each area of concern orthogonally, and to then use co-design tools to produce integrated designs and implementations that achieve substantial synergy and better reflect the underlying physical environment of the sensed system. The objective of the work was to extend the notion of hardware/software co-design into multiple dimensions through the application of existing techniques, such as Aspect Oriented Software Development methods in which the final system design is generated by weaving together the individual components with appropriate software/firmware "glue" to achieve the requisite integration and reap synergistic benefits. This generation phase would be optimised with respect to a combined cost function (which would seek to aggregate data early but minimise power consumption during operation) for the target system. It was envisaged that iterative specification/integration would be required to maximise synergy.

Anticipated outcomes for the project were specification languages for each dimension, tools for producing integrated designs from orthogonal designs, formal validation mechanisms for each dimension and for integrated system specifications, tools for selecting optimal designs given a global cost function and mechanisms for managing a running system based upon the global cost function.

3.1 Co-Design Approach

The work described in this thesis was carried out in the context of the DIAS-MC objectives and concentrates on the trend in Wireless Sensor Network applications with increasing node density and multi-hop communications. This results in challenging design constraints which contribute to the global cost function outlined in the overall DIAS-MC context. Formal validation and assessment of the communications contributions were an essential element of the work undertaken for this thesis which, in itself, required the development of a flexible cross layer architecture (XLCA) for the design and assessment of adaptive communications protocols. This design tool is fully described in the next Chapter 4 after the main elements which it was designed to exercise have been outlined.

The cross layer co-design issues associated with the communications aspects of this work are shown in Figure 3.1. The elements in this figure will be described in a conceptual way prior to the description of XLCA.

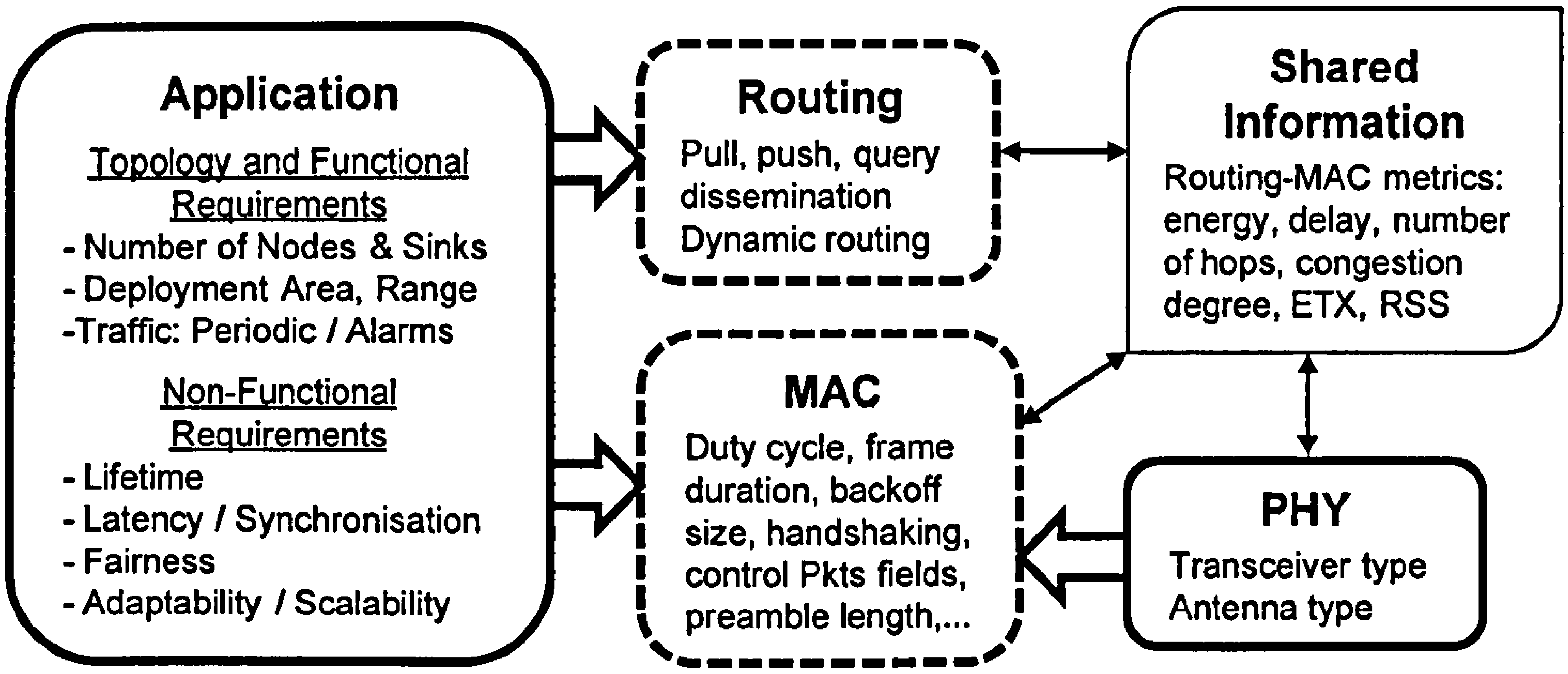

Figure 3.1 – Cross-layer inter-dependency and co-design

In order to illustrate the potential communications problems that arise in an adaptive wireless sensor network design, Figure 3.2 shows a possible application that requires multi-hop communications to gather data from the sink located in the centre (). Every node has the same omnidirectional (OD) range (slotted circle around the sink). The nodes share the same frequency channel and active times for communications; due to the limited range the nodes require the use of multi-hop routing represented with the red arrows.

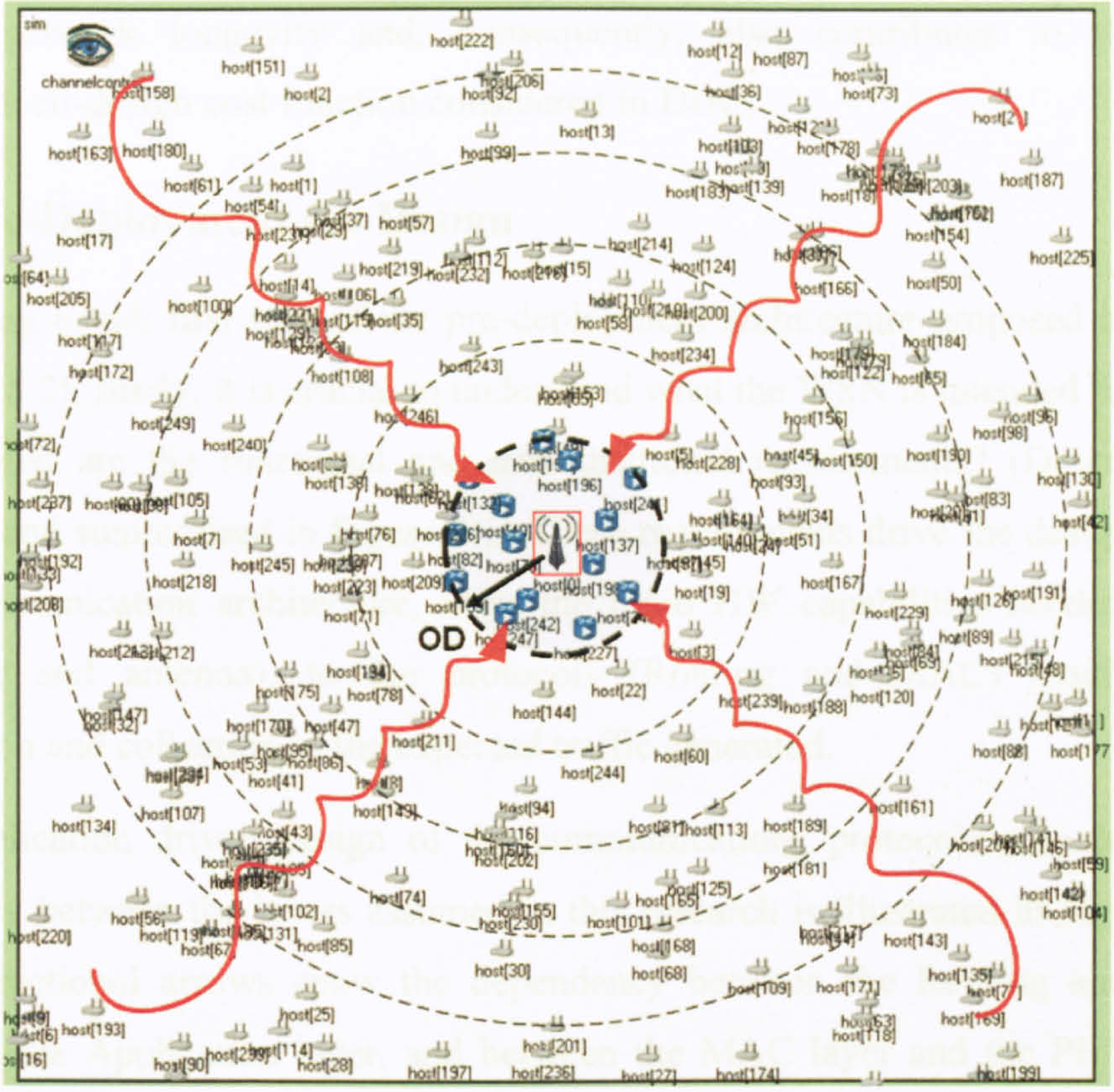

Figure 3.2 – Nodes-to-sink sensor network with 250 nodes (one-hop nodes ▣)

Observation of such networks can elucidate the principal communications design challenges that have been described along the Chapter 1 , which are listed in the motivation Section 1.6.1. Broadly, these design challenges can be summarised in three aspects:

- network interconnection with self-configuration and routing,
- network operation to carry data communication with avoidance of congestion problems in the control access and,
- network adaptation to changes in the application requirements, traffic conditions and topology.

These aspects consist of the design of the communication system that requires the consideration of a pre-deployment and a post-deployment architecture. Most of the prior WSN work has not been done from the pre and post deployment perspective; this thesis emphasises the fact that post deployment adaptability is essential to maintain network longevity and, consequently, also contributes to the pre-deployment co-design cost function considered in DIAS.

3.1.1 Pre-Deployment Co-Design

According to the first step of the pre-deployment architecture proposed in DIAS (Section 1.5.2), firstly, it is crucial to understand what the WSN is intended for, to be precise, what are the functional and non-functional requirements? (Described in Chapter 1 and summarised in Figure 3.1) These requirements drive the design of the entire communication architecture, from the radio HW capabilities needed (radio transceiver and antenna), to the protocols (Routing and MAC) required for transmission and collection of the expected traffic generated.

The application driven design of the communications protocols and the inter-dependency between the layers assumed in this research is illustrated in Figure 3.1. The unidirectional arrows show the dependency between the Routing and MAC layers and the Application layer, and between the MAC layer and the PHY layer. The bidirectional arrows show the exchange of information between layers via the shared information database shown in Figure 3.1. In particular, cross-layer design enables account to be taken of Routing/MAC parameters that can be tuned (post-deployment) during the network operation in order to satisfy the application requirements (made available through a common service or interface).

In the design of the pre-deployment architecture, a main constraint is the limited energy supply and an overall concern of WSN research has been the design of more energy-efficient communications systems. This purpose has certainly been tackled with a wide range of solutions implemented at different layers of the communications protocol stack. These solutions include proposals such as in-network processing and aggregation of the application generated data, energy-aware routing, low-power MACs and efficient radio transceivers. However most of these approaches have attempted to optimise the power consumption of one component of the overall communication system in an isolated fashion. In addition, the design of these particular solutions is usually directed to obtain the required functionality and performance of each component in question, but not the overall functional and non-functional requirements of the targeted applications (e.g. the WSN in Figure 3.2 or those shown in Figure 1.1).

Without a proper understanding of the interactions and tradeoffs that these one-off solutions entail to the overall system, the benefits of one solution can, actually, restrict those of another. Hence, it is becoming evident the importance of co-designing the different elements (SW and HW) that take part in the network communications. As indicated in Section 1.5, co-design is a methodology that attempts to optimise the network performance with an integrated design of orthogonal aspects; for example co-design of the Routing and MAC protocols.

From the energy perspective, for example, it is important to identify how the overall power consumption is related to the design parameters of every layer involved in the communications processes. Important parameters at each layer are:

- the traffic generated at the Application layer,
- the routing decisions and maintenance overhead of the Routing (Network) layer,
- the control access method, congestion avoidance mechanisms and power management (duty-cycle) of the MAC layer and,
- the transceiver configuration (frequency, output power, data rate, sensitivity) and the antenna pattern (gain) at the Physical layer.

Consideration of all these aspects is needed for co-designing an integrated communications system, which must be responsive to the application requirements such as lifetime, coverage, data rate, latency or scalability, among others. As described in Section 1.3, these requirements are very interrelated and the co-design process should consider them in unison to compensate for tradeoffs between each other.

With the Hardware choices fixed at the start, the type of application (periodic monitoring, alarms) and the specific requirements (lifetime, goodput, latency) will have an impact on the pre-deployment design of the routing and MAC protocols (see Figure 3.1). The intention of this research is to use cross-layer techniques to integrate the design of adaptive communications protocols and to exploit the capabilities of the

Physical layer, the final aim being to meet the requirements while minimising the energy consumption. The main cross-layer techniques that have been proposed in this thesis are introduced in Section 3.2. Prior to their introduction, it is important to consider the post-deployment conditions in WSNs that impose important limitation in the co-design of an optimal pre-deployment architecture.

3.1.2 Post-Deployment Co-Design

In nodes-to-sink multi-hop WSNs, such as the network shown in Figure 3.2, the high diversity of traffic conditions and neighbouring environments (e.g. edge nodes Vs one-hop nodes) presage that the pre-deployment choices cannot suit the actual network conditions (traffic load, congestion, buffer occupancy, etc) of every single node in the network. However the functionality and settings of such layers are commonly predetermined from the pre-deployment design and thus the adaptability of the network is very restricted. Therefore it is important in this kind of network at the very beginning, to provide means of adaptability for the pre-established network protocol parameters. Moreover, as a result of the distinctive constraints of the low-power devices and deployment scenarios considered in WSNs, sensor nodes are likely to operate under changing conditions in the state of the network such as variation of the traffic load, neighbour failures or link disruptions. In addition the network user may decide changes in the application requirements to be conducted autonomously at running time. All these changes do not only affect the Routing-MAC design parameters, but may need to be considered in the pre deployment design of higher layers' functionality. For example, the co-design of the Query processor, the objective of which is to optimise the generation and aggregation of packets in the multi-hop paths of a network, will need to consider changes in the state of the network such as congestion at the MAC access or disruptions in the routing due to neighbour and link failures.

The implementation of co-designed schemes with the use of cross-layer information and joint capacities at different layers can be used to rapidly detect and accommodate those changes.

This thesis concentrates in the Post-Deployment architecture and investigates the co-design of new techniques in WSNs that can provide adaptability and as a result increase longevity of the network. These adaptive techniques cannot be easily captured inside of analytical cost-functions due to the unpredictability of their use across the network (e.g. dynamic Routing in specific hot-spots with higher traffic). However, the post deployment adaptability contributes to the global cost-function, a *posteriori*, with the prolongation of the operational network lifetime.

Looking at the literature, limited research has been carried out to benefit from cross-layer interactions for the design of post deployment procedures that first, provide adaptability in order to preserve the applications requirements, and second, provide enhancements in the operational network lifetime (longevity).

3.1.3 Co-Design Objectives

While DIAS attempts to integrate the design of the HW system and all dimensions of the SW system, this research work focuses in the co-design of adaptive communications protocols regarding the shared access to the channel and the radio HW capabilities (transceiver and antenna). This is essentially the communications aspects the main problem being to be able to fit the communications choices to specific requirements of WSN applications (Figure 3.1).

In addition, the main approach in DIAS (as described in Section 1.5.2) has been the integration (co-design) of available solutions from the "Library" (parameterised with a series of cost-functions) inside the pre-deployment architecture to optimally meet the application requirements; in the hypothetic case that these cost functions can be extracted and integrated. However network dynamics in WSNs such as congestion problems, link disruptions, node failures, traffic load and topology changes can prevent the application's requirements from being achieved. Consequently, this thesis focus in the provision (a *priori*) of adaptive techniques (smart antennas, hybrid MACs, proactive schemes) designed to provide post deployment adaptability.

Consequently, the solutions that have been investigated, in addition to considering the Pre-Deployment network conditions and requirements, seek to provide Post-

Deployment adaptability in view of the expected network dynamics over extended periods of time. The main objectives of the co-design, which is the methodology used to achieve the General objectives (1.7), are summarised next:

1. Exploit cross-layer interactions with information exchange and integration of functionality in the Application, Routing and MAC layers in order to:
    a. maximise synergy and flexibility of the sensor network system,
    b. meet the application requirements more efficiently in terms of the energy consumption (i.e. increase the network operational lifetime) and,
    c. facilitate the detection and adaptation of network dynamics such as node failures, topology changes and traffic load requirements.
2. Combine adaptive MAC techniques aware of the traffic conditions and radio hardware capabilities (transceiver and antenna device) with the main purpose of minimising intrinsic problems of the contention access in WSNs such as congestion and the funnelling effect.

3.2 Adaptability and Longevity (Post-Deployment)

The main adaptive procedures that have been considered in the post deployment architecture that will be proposed and implemented in this thesis are listed below:

- Adaptive MAC schemes to adjust the original design parameters (e.g. the duty-cycle) according to the actual post deployment operation conditions (e.g. traffic load or level of occupancy of the radio channel).
- Dynamic Routing strategies triggered at the MAC layer to confront network dynamics.
- Cross-layer techniques to reduce sources of energy wastage (those explained in Section 1.4) during the sharing access of the radio communications process.
- Failure management proactive schemes with the use of cross-layer techniques in the detection and circumvention of energy-vulnerable nodes.

These cross-layer techniques, in addition to providing the necessary adaptability, have the design goal of maximising the longevity of the system. This has necessitated the integration of energy usage minimisation which in addition to provide network adaptability, optimises the use of radio and battery resources. In order to achieve these objectives it is necessary to reduce the impact of the sources of energy-wastage and failure in multi-hop WSNs: congestion in the channel access, the funnelling effect and the existence of energy-vulnerable nodes (explained in Section 1.4). These solutions can be classified into three categories:

1. Contention MACs with **directional antennas** to reduce congestion problems promoted from the OD transmissions during the contention access.
2. Localised **hybrid access** at the sinks to reduce the funnelling effect.
3. **Proactive schemes** to postpone failure of energy-vulnerable nodes.

In order for these techniques to operate there are fundamental requirements associated with WSNs; in Chapter 4 the required environment and assumed attributes are described. In the following, the main adaptive techniques are introduced and will be covered in detail in Chapters Chapter 4 , Chapter 5 , Chapter 6 and Chapter 7 .

3.2.1 Adaptive MAC design

The design of the communications protocols is directed to provide adaptive functionality to cope with different applications demands. In particular, the access control protocol is of interest because it interacts with both the routing and PHY layer and provides the main means for adaptation: sleeping schedules can be varied, duty cycle and frame duration can be changed, neighbour discovery is performed and failure detection and re-routing can be carried out.

Pre-Deployment requirements: At the start of the network operation the MAC parameters such as duty-cycle, frame duration, backoff size, etc (shown in Figure 3.1) of every node are selected to provide a network operation that meets the initial requirements (e.g. lifetime, latency) at a particular network deployment (e.g. the network shown in Figure 3.2). At pre-deployment, the network user establishes the initial traffic requirements and desired network size (area and number of nodes) which permits to estimate, a priori, the design parameters based on previous deployment experiences. Due to the nature of multi-hop networks, the initial MAC choices seek to assure the communications process of the highest load traffic, which eventually is expected in nodes close to the sinks. However these choices entail energy wastage in nodes with lower traffic requirements and adaptive mechanisms are proposed to optimise the use of the radio resources. In particular, the duty-cycle, and thus active time of any node, may be locally adjusted to the actual traffic conditions of each node in the network.

3.2.2 Integration of Routing and MAC

Routing adaptability Post-Deployment: With the assumption of nodes-to-sink applications, the Routing layer has to interconnect the network so that each node has at least one neighbour to which directing the traffic flow that converges on one of the sinks. In this thesis, a "fusion layer" approach is proposed where routing and MAC are merged together. The initial routing decisions provided by an initialisation stage will change, depending on the MAC congestion metrics in a particular node but also from other neighbours and routes towards the sinks. This information may be passed in a sequential forwarding process within MAC control packets (CTS or ACK). With integrated Routing and MAC functionality, dynamic routing strategies are proposed to optimise the network performance and to circumvent node failures. The localised routing decisions are initiated at the MAC layer which is the first element on detecting problems (packets losses or failing neighbours) during the communications process. In addition the MAC has access to the signal measurements provided by the radio transceiver and to the information of the control packets, and manages the transmission and reception of every packet.

3.2.3 Cross-Layer Techniques to Extend Network Lifetime

When the overall objective is to minimise energy consumption this infers that the wake/sleep duty cycle should be as small as possible. Under decreasing active times, efficient contention MAC protocols attempt to maximise the use of the shared channel to achieve application requirements (throughput, latency, lifetime) but using minimal resources. Consequently, with an increasing number of nodes and multi-hop communications, congestion problems are likely to appear during the competition access in the entire network; as for example in the network shown in Figure 3.2. More precisely, due to the funnelling effect, nodes that are closer to the sinks become more saturated with the forwarding task but with reduced chances of competing for access to the channel. These nodes restrict the network time operation and congestion problems can prevent the application's requirements from being achieved, primarily resulting in additional delay, or packet loss in the event that node buffer capacity is exceeded.

Several cross-layer techniques are proposed in this thesis to maximise the network lifetime while the cited application requirements are preserved. Some proposals attempt to reduce the congestion problems in the whole or some parts of the network; others are directed to circumvent energy vulnerability on specific nodes in the network. The major contributions to the DIAS-MC co-design philosophy are introduced in this section and will be described in detail in Chapters Chapter 5 , Chapter 6 and Chapter 7 .

3.2.3.1 MAC Co-Design with Directional Antennas

In relation to the antenna device, current WSNs solutions assume the use of omnidirectional (OD) antennas which allow broadcast Tx/Rx essential for neighbour discovery and MAC contention mechanisms. However network performance could profit from the use of directional antennas which have the potential to increase range as a result of their inherent antenna gain and to minimise interference due to the restricted antenna aperture. Adding the pointing capability, directional antennas can notably increase the potential for spatial reuse achieving higher throughput but lower energy consumption. Adoption of directional antennas in WSNs requires a careful design of the MAC protocol and consideration of the actual antenna radiation patterns in order to profit such directional capabilities.

In this research, the MAC co-design with directional antennas installed in every sensor node aims to reduce the congestion problems, such as collisions, retransmissions and overhearing, those are significant in the entire network. The objective of decreasing congestion is to reduce the waste of radio resources and increase the spatial reuse (simultaneous non-colliding transmissions), with the overall result of needing smaller active times to achieve the applications requirements (longevity).

In Chapter 5, the directional contention access mechanism (*Dir*C-MAC) introduces the use of directional transmissions in sensor networks. Co-design techniques of traditional handshaking contention mechanisms (RTS-CTS-DATA-ACK) with combination of ominidirectional (OD) and directional transmission/reception are proposed in order to provide the same network functionality with respect to MAC solutions using OD antennas. According to the antenna requirements and suitability of antenna technologies in WSNs, this research proposes the use of switched beam directional antennas such as the MaxBeam [79] that are modelled in Section 4.1.8.

The fact that the pure contention access used in *Dir*C-MAC is constrained in order to decrease congestion close to the sinks because of the funnelling effect has motivated the investigation of hybrid MAC procedures.

3.2.3.2 Co-Design of a Hybrid Access Mechanism

With nodes-to-sink routing and shared radio access time for communications, the congestion problems derived from the funnelling effect in multi-hop networks imposes an important capacity limitation in the MAC design. The use of a TDMA-based MAC protocol can be considered to carry data link communications without collisions. However, creating and maintaining a TDMA schedule in a multi-hop nodes-to-sink application can be extremely complex if slots need to be allocated more than one-hop away. The effect of clock drift can also be considerable with low duty-cycle MACs as can topology changes or node mobility. In such situations network design can scale more easily using a contention-based protocol than a TDMA-based solution.

In order to reduce the funnelling effect while maintaining the scalability and flexibility features of a shared contention access the use of hybrid access mechanisms is proposed (contention handshaking and TDMA). As part of a hybrid MAC, the co-design of a novel access control protocol is proposed that consists of the formation of TDMA clusters at the sinks, the size of which can be extended by the use of switched beam directional antennas. The adaptive hybrid protocol is called SSAS, Scheduled Sectorial Access at Sink, and will be explained and evaluated in Chapter 6. With scheduled access at the sinks in SSAS, the idea is that one-hop nodes do not need to compete accessing the sink and can remain receiving packets during the contention active periods. As a result, the accessibility towards the one-hop area is increased and the congestion associated to the funnelling effect is reduced; hence smaller active times are required and the network lifetime can be increased.

3.2.3.3 Cross-Layer Proactive Schemes for Energy-Vulnerable Nodes

The use of adaptive MAC schemes, directional antennas or the adoption of hybrid MAC techniques can increase the network lifetime and improve the fairness on distribution of energy consumption across the network. However, the existence of energy-vulnerable nodes, those that consume energy faster, is an intrinsic problem of multi-hop networks. The non-uniformity of energy consumption is caused by the unequal impact of the mentioned congestion problems and funnelling effect across the network. The vulnerable nodes are usually chief participants in the forwarding process of data packets towards the sinks and their premature failure can leave unconnected regions from the sink.

In order to enhance the Post-Deployment Adaptability, the intention in this research is to co-design proactive failure management schemes with the use of cross-layer techniques to enable early detection and actuation in order to postpone failure of energy-vulnerable nodes. The cross-layer techniques that will be described in Chapter 7 include the use of:

- localised hybrid MAC with scheduled access from senders to maximise the sleep time at the energy-vulnerable nodes.
- dynamic Routing strategies co-designed with the MAC to balance the traffic load that is sent to the vulnerable nodes with other close neighbours.

These proactive schemes use cross-layer information exchange and are autonomously initiated at the most vulnerable nodes. In particular, the use of physical layer information to evaluate the rate of battery discharge allows the detection of energy vulnerable nodes.

3.3 Evaluation Methodology

The cross-layer design techniques introduced in Section 3.2 have been progressively identified following a gradual process of logical design. This chapter introduces the methodology for co-design and assessment that have led to the development of the communications architecture XLCA that is described in Chapter 4 . XLCA is an environment used to assess and optimise the cross-layer techniques introduced in Section 3.2 which are candidates for post deployment adaptability. These techniques form a contribution, in terms of global cost function, to the pre deployment co-design process in the DIAS-MC project. Therefore the emphasis of this thesis is the refining of these techniques prior to the overall co-design operation. Figure 3.1 shows the main elements of the communication system that need to be considered in the implementation of the complete communications architecture. In order to accommodate these elements there are a series of requirements which are described in the XLCA architecture proposed in Chapter 4 .

With the intention of co-designing, modelling and evaluating communications solutions three types of methodologies have been used in WSN research: analytical, experimental and simulation.

An initial research strategy considered the **analytical** characterisation of available software and hardware communications solutions in WSNs; the aim being to identify analytical cost functions (one of the DIAS objectives) that describe the network performance (non-functional requirements) with the consideration of the interactions that take place between the communication components. For example, in a nodes-to-sink periodic monitoring application, with a known data rate and average number of hops in the network for the given routing scheme, a cost function could estimate the required use of the radio device by the MAC protocol, and thus calculate the energy consumption. Comparison of cost functions over different set of solutions could help to identify tradeoffs to be used in the co-design of a more efficient communication system, which is aim of this thesis. The efficiency is evaluated in terms of the application requirements (lifetime, latency, overhead ratio, etc) and thus different cost-functions are needed for each parameter. However, if more than a pair of nodes is considered, the complexity of the component interactions to be measured in the cost functions is at such magnitude that an analytical approach is not feasible. Nevertheless, the multitude of design challenges imposed on sensor networks tend to be quite complex and usually defy the analytical methods because of WSN-specific constraints like limited energy and the sheer number of sensor nodes. A different approach is to use an **experimental** methodology to implement cross-layer architecture and to test, a *posteriori*, the effectiveness of the previously co-designed solutions. Real world implementations and test beds are the most accurate method to verify the designs and concepts but testbeds are not yet practical for large scale WSN experiments; testbeds impose strong constraints on the network both in terms of topology and size. Furthermore the cost of running an experiment on a testbed, in terms of setting-up the experiments, instrumenting the nodes, gathering the metrics on the performance, etc. is much higher than on a simulation and thus the simulation remains the most practical tool to obtain a feedback on the performance of a new solution. Nevertheless, it is possible and advisable to use conclusions from real experiments in the modelling of the physical layer, such as response time and power consumption of transceivers, signal measurements of the radio channel and antenna radiation patterns.

Accordingly, the approach was changed and the modelling of a Cross-Layer Design Framework inside a **simulation** tool was selected as the co-design and assessment method. In this thesis, simulation is considered an appropriate means of assessment because the need of testing different topologies, large networks in size and number of nodes, changing application requirements, and most important, the validation of the cross-layer developments that are to be proposed. Furthermore simulations enable the iterative specification/integration of different solutions which is the base for co-design optimal solutions.

Inside the framework, the idea has been to design flexible cross-layer communication architecture for a broad range of applications, on top of which solutions at different layers can be tested via simulations for co-design purposes. The architecture can adopt any application, routing, MAC or use different hardware platforms, providing that every component supplies the information required from the other layers (e.g. the routing protocol needs to be updated with the MAC congestion metrics). In order to evaluate the interaction of the different components during network operation, proper modelling must be included in the framework. Moreover the framework must provide, explicitly, means for cross-layer information exchange and a complete set of performance and congestion metrics. In this manner the cost functions, implicitly considered in the architecture, can be extracted from the simulations results. The co-design process is summarised in the next steps which can be visualised in Figure 3.3:

1. Select an application and define its functional and non-functional requirements.
2. Propose an initial co-designed communication solution (SW-HW) that is expected to satisfy the application requirements. Model and implement the components within the framework, adjust the design parameters and extract results.
3. Analyse the impact of the design parameters of each component in the network on performance. Identify challenges, operation problems and trade-offs. Co-design new solutions and implement them within the simulation framework.
4. Verify the new solutions under changing conditions and application requirements, if not satisfactory, return to step 3.

To accelerate this process, the assumed strategy sets some of the components, such as the routing scheme and the radio hardware, and focuses on analysing the behaviour of another component, e.g. the MAC, with changing application requirements.

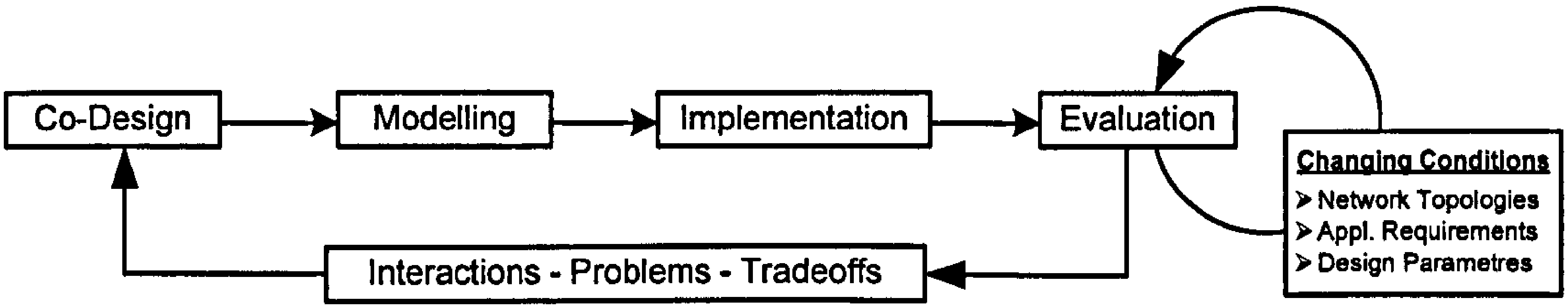

Figure 3.3 – Iterative process for the co-design and assessment of communication protocols

With this approach, a base Cross-Layer Communications Architecture (XLCA) has been developed within which different solutions have been co-designed as described in Chapters Chapter 5 , Chapter 6 and Chapter 7 . Figure 3.4 illustrates the different cross-layer developments (those introduced in 3.2) over the base architecture XLCA. The proposals have been devised after investigation of network problems and challenges identified by the assessment of the XLCA architecture in different scenarios and under different application requirements. The protocols are designed sequentially, where the results of one have led to the design of the next one, and with all of them integrated together in the cross-layer overall architecture XLCA (illustrated in Figure 3.4).

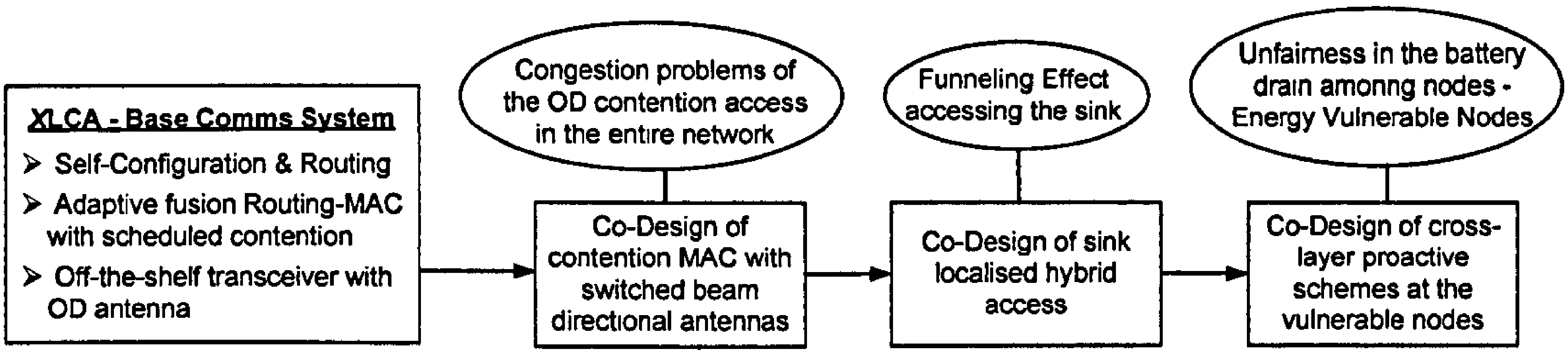

Figure 3.4 – Evolution of Co-Designed Protocols for WSN Communications

In addition comparison has been made with respect to the base XLCA MAC solution (scheduled contention similar to S-MAC [28]) and also other protocols, such as B-MAC and LEACH, to gain more insight into the actual performance improvements.

The evaluation environment of the XLCA architecture, which has been defined and refined, to accommodate the adaptable techniques proposed in Section 3.2 is described in Chapter 4.

Chapter 4

The Evaluation Environment

The overall objectives of adaptability and longevity have been accommodated by adaptive MAC systems, pro-active methodologies and energy reducing devices. These techniques are described in detail in Chapters Chapter 5 Chapter 6 and Chapter 7 . However in order for such techniques to be operational in specific WSN architectures there is a requirement for the existence of several support mechanisms within the overall system specification. These support mechanisms are incorporated in a cross layer communications architecture (XLCA) which has been enhanced to provide the desired functionality required by the adaptive and life extending techniques.

This architecture is modelled and implemented in the discrete-event simulator OMNeT++ to provide the "tool" that has been used to assess the overall performance of the cross layer developments. The XLCA architecture is described in Section 4.1.

4.1 Cross-Layer Communications Architecture (XLCA)

In order to develop this communications architecture, the design is directed from the high level application requirements down through the low-level hardware requirements. The main requirements of the XLCA needed to assemble a robust simulation environment are to provide:

- The accommodations of a network of any size and number of nodes with at least one sink.
- An Application layer to generate packets according to the user requirements.

- A “fusion” Routing-MAC layer that provides the main functionality for the network communications (self-configuration and routing, data link communications and adaptability post deployment schemes).
- A Physical layer that models the transmission and reception of packets with the consideration of the radio transceiver parameters, radiation pattern of the antenna, path lost and interferences in the channel. The Physical layer also requires a battery module to account for the energy drain at the different operation modes of the sensor nodes during the network lifetime.
- A means of cross-layer information exchange to maintain and update important information needed in the operation of the cross-layer techniques in every particular node. This information includes:
    - Operation state, Tx power and link measurements of the radio transceiver.
    - Configuration state of the directional antenna (if such is available).
    - Battery level that updates itself with respect to the transition of operation modes during the nodes lifetime.
    - MAC and Routing metrics (Figure 3.1).

A representation of what needs to be modelled and the main functionality that is provided in the cross-layer architecture XLCA is shown in Figure 4.1.

Network Communications Models in XLCA

Description of the functionality encompassed in the merged Routing-MAC layer has been divided in four sections: Initialisation: Self-Configuration phase, Next-Hop Adaptive Routing, Base Contention-MAC (C-MAC), Adaptive Schemes: Post-Deployment Requirements.

4.1.1 Application Layer (Traffic Generation)

This thesis concentrates in multi-hop nodes-to-sink applications. Depending on the traffic, typical sensor applications can be separated into event-driven and time-driven applications.

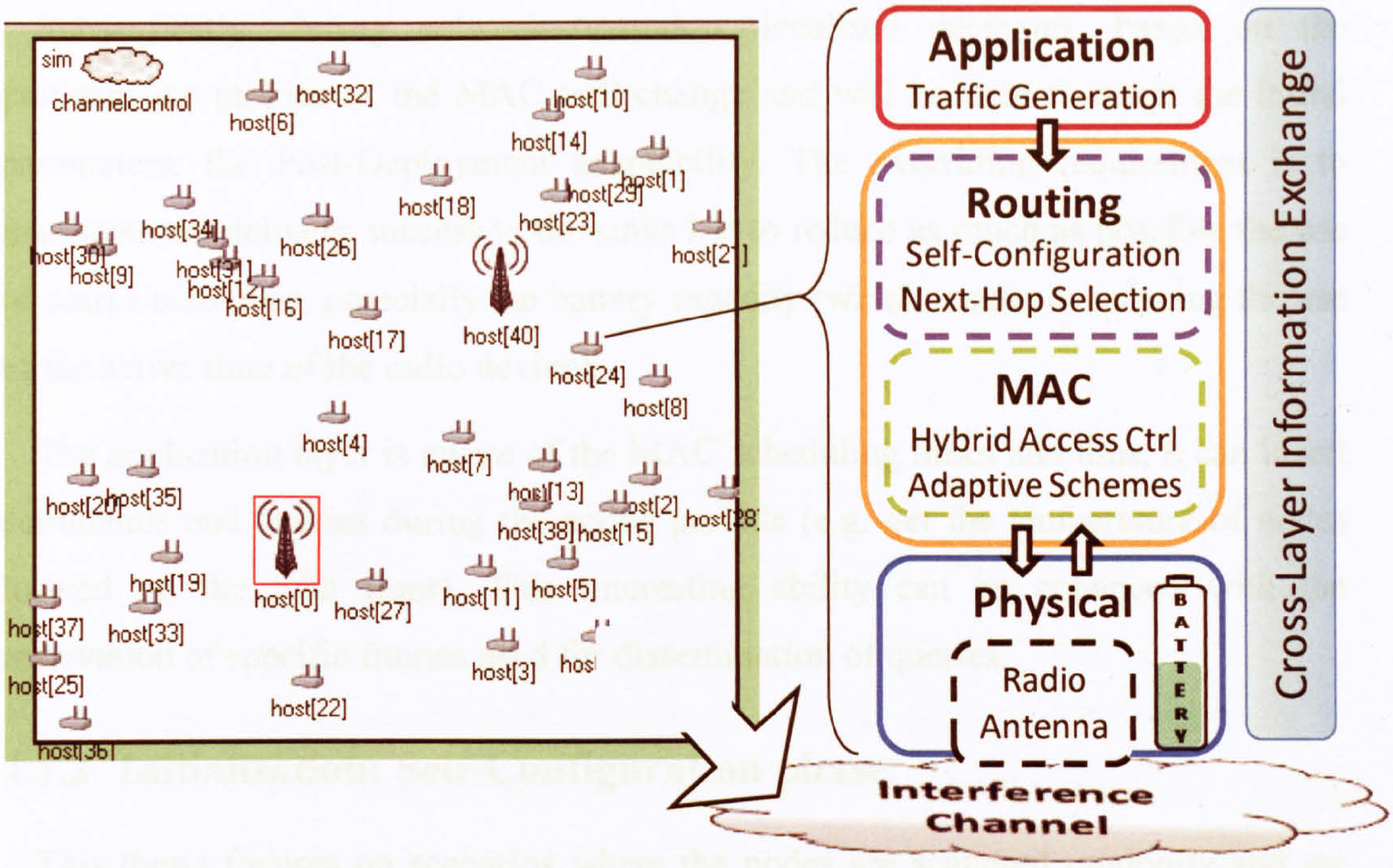

Figure 4.1 – Modelling of the Cross-Layer Communications Framework

Event-driven applications refer to either casual event detection or emergency event detection (e.g. alarms), whilst time-driven applications consider periodic monitoring from the nodes. Depending on the periodic monitoring application, the frequency of the generated sensing data can differ significantly, for example with records every one second to several minutes. Any of these application types should be accommodated in the architecture proposed but they usually have different priorities such as delay sensitivity, acceptable data loss, network lifetime and fairness, thus the choice of routing/MAC parameters and mechanisms will differ. In particular it is important to define the expected traffic patterns and rates that will decide the design parameters of the Routing-MAC fusion layer, these are the Pre-Deployment choices.

The basic idea is that during the network initialisation, and whenever the applications' requirements change, the sinks inform the network with the routing/MAC parameters that are expected to achieve the specific functionality, a priori, for the application type and topology considered. The broadcast process in which this information is distributed also enables the setting up of routing trees towards the sinks.

Subsequently, during network operation, localised decisions, based on the performance metrics of the MAC will change and will be used to adapt the initial parameters; the Post-Deployment adaptability. The overriding requirement is to maximise the delivery success to the sinks but to reduce as much as possible the use of scarce resources, especially the battery capacity (which results in reducing the use of the active time of the radio device).

The application layer is aware of the MAC scheduling times and thus, it can insert commands and queries during the active periods (e.g. get the temperature of nodes located on the fifth floor). This interesting ability can be enhanced with the reservation of specific frames used for dissemination of queries.

4.1.2 Initialisation: Self-Configuration phase

This thesis focuses on scenarios where the nodes are scattered randomly and are application unaware when network life begins. In these scenarios a mechanism of self-organisation is necessary, firstly, to broadcast from the sinks the pre-deployment application requirements and Routing/MAC settings, and secondly, to allow for neighbour discovery and the establishment of routing paths towards specific destinations (the sinks). Because a configuration stage is needed at the Application and Routing-MAC layers; it is proposed to unify this process with the use of a single packet (called Routing packet, shown in Figure 4.2) that contains the information required by both layers. In order to minimise the number of multi-hop transmissions, an initial routing decision is the selection of the next-hop that provides the shortest-path and minimum-distance towards one of the available sinks.

Considering nodes-to-sink applications with the collection of data at one or more sinks, the selected approach presented here is based on tree creation initiated by the sink(s). The process on which routing trees are established has similarities with the one phase pull directed diffusion routing mechanism [66]. Each sink sends one routing packet to its neighbour nodes that in turn re-transmit the packet, just once, until it has reached the leaves nodes. Each node adds routing information to the sink packet as number of hops and the Radio Signal Strength Indicator (RSSI) measured at the radio transceiver. The routing is a localised routing algorithm (LRA), where only information from one-hop neighbours is used and it adopts a sequential forwarding decision mechanism [85] that avoids problems of plain flooding, such as closed loops or unheard neighbours due to collisions of the routing packets. For each packet received from a neighbour a new entry is made in the Neighbour Table (shown in Figure 4.2) which information is used for routing decisions. In order to make proper routing choices the routing process is made sequentially where nodes at (n+1)-hop wait enough time before retransmission enabling all n-hops' nodes to send their routing packets. Possible collisions between the same n-hop nodes' transmission are avoided by generating backoffs dependent on the nodes' unique ID.

Routing packets are sent at maximum transmit power in order to reach the maximum number of neighbours at each broadcast and establish the shortest tree in terms of number of hops. Initially a shortest hop and minimum distance routing decision is made at n-hop nodes from the (n-1)-hop neighbours that have been detected. The next-hop selection is made first picking up the neighbour(s) with minimum number of hops to any of the sinks, and from these, the one with maximum RSS detected in the reception of the routing packet.

In addition to the application requirements from the user (maximum acceptable delay and packet inter-arrival rate), the routing packet that is illustrated in Figure 4.2 contains the following fields:

- the ID of the sender node and the ID of the sink,
- duration of a superframe (Frame Duration),
- duty cycle (i.e. rate between the wake and sleep time inside the Frame Duration),
- time of the next beginning of superframe use to impose a sleeping schedule shared by all the nodes at the beginning of the network operation (Next Frame),
- the number of hops from the sender node to the sink.

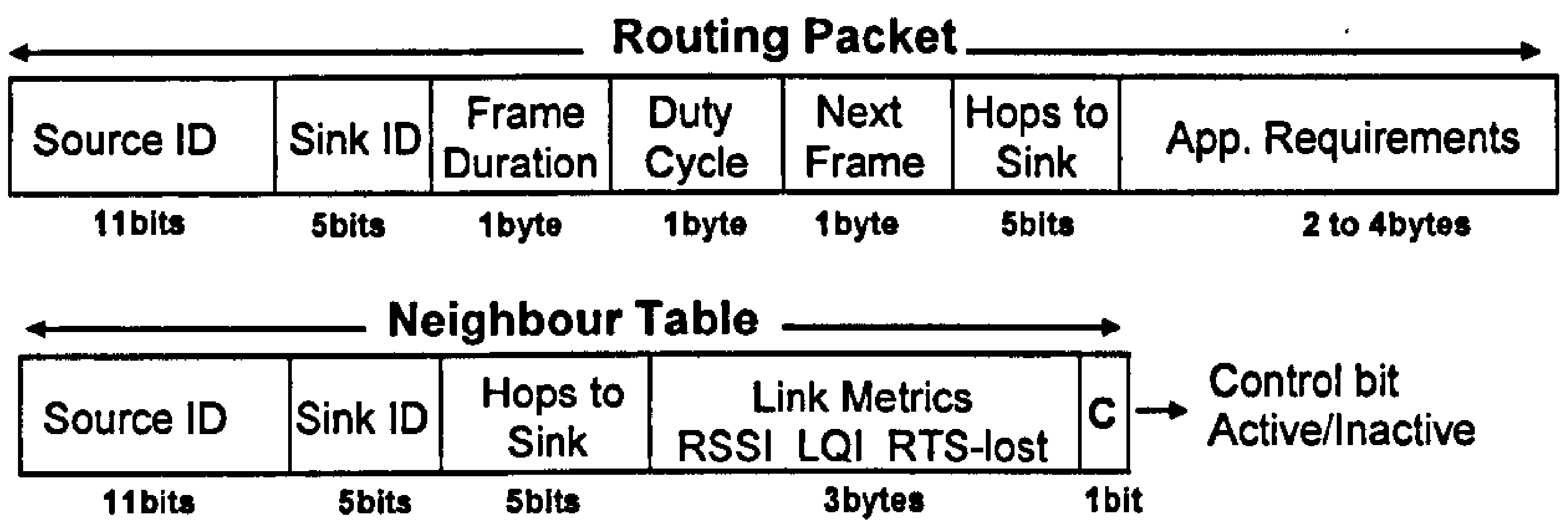

Figure 4.2 – Routing Packet (R) structure and Neighbour Table content

4.1.3 Next-Hop Routing

As indicated in Section 3.2.2, the co-design approach adopted in XLCA merges Routing and MAC layers (fusion layer). Being aware of the potential next-(*n*-1) hop neighbours after initialisation, routing strategies at nodes are performed autonomously using congestion metrics distributed by the MAC control packets, therefore the use of extra routing packets is avoided. The nodes forward their packets using sequential forwarding [85] towards the sink. Energy is invested in every packet when it is routed through every node. Therefore, the longer a packet has been routed, the more expensive it is to drop that packet. The queue strategy sets higher priority to the packets that have been more time in the network. However, if this time is higher than the maximum expected delay the packet is discarded.

One-hop away neighbours' information is sufficient for the routing decisions, which avoids the flooding of overhead control packets. If there is more than one sink, the nodes select the sink that is closest to them (see Figure 4.1). Nevertheless, the neighbour table (Figure 4.2) contains information about all the neighbours regardless of the sink they are connected to. Hence, if a node becomes disconnected from its sink, it can select a path that will connect it to another sink. Additionally the "fusion layer" supports topology changes (due to node failure or addition of nodes) by re-routing the traffic if the current next-hop does not reply and by adding new nodes to the neighbours list if control packets from this are overheard.

As initially shown in Figure 3.1, the information that has been considered here for routing purposes is based on measurements performed at the MAC or PHY layer: the received signal strength indicator (RSSI), number of hops towards the sink, delay, expected retransmissions (ETX), congestion degree, etc are exploited to select the best next hop. The information is added onto the control packets at the MAC layer. The results presented in this thesis will only compare routing strategies for failure management and this takes place in Chapter 7 . However several dynamic routing strategies[1] are possible with the combination of these metrics; some of these have been evaluated in [86].

4.1.4 Base Contention-MAC (C-MAC)

The base medium access control mechanism in XLCA is a scheduled contention MAC, referred as C-MAC. In essence, C-MAC is similar to the well known Sensor MAC (S-MAC [27]) using scheduled contention and four-way handshaking. As shown in Figure 4.3, the scheduled contention for data communications occurs during the active (Act) times, which alternate with the Sleep periods every "Frame Duration" time. The scenarios that will be assessed in this thesis will consider a periodic monitoring application with data packets generated every fixed period called "inter-packet arrival time" (see Figure 4.3). In any node, after the initialisation stage, the instant in which the first packet is generated is a random value between 0 s and the inter-packet arrival time.

Moreover C-MAC adopts an Adaptive Sleeping mechanism to locally adjust the duty-cycle (explained in the next Section 4.1.5), an improvement that has been also considered in T-MAC [44]. In addition, compared to the frequent "sync" packets required in S-MAC, the synchronisation of C-MAC profits the sequential-forwarding of MAC control packets (RTS and CTS) to propagate from the sinks to the entire network the time synchronisation of the wake/sleep periods.

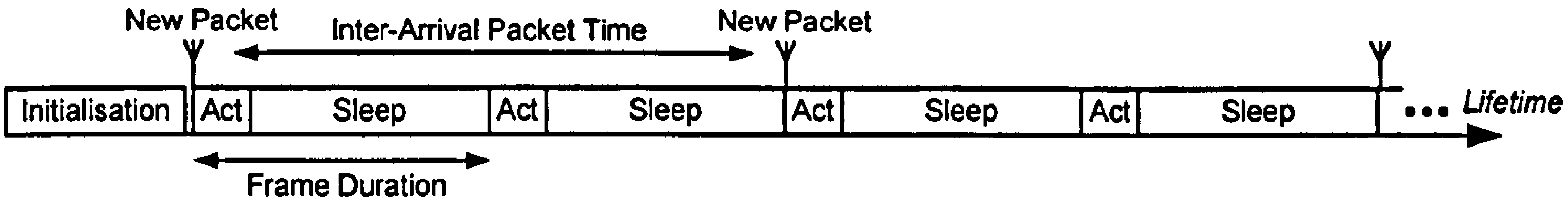

Figure 4.3 – Timeline of the Scheduled Contention operation in XLCA

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[1] A parallel study of dynamic routing was carried out, within the DIAS-MC project, by Dr. Florence Kolberg [86].

The main constraint that the physical layer imposes on the MAC is the energy consumption, restricting the active time available for radio communications. Off-the-shelf WSN transceivers such as the CC2420 [43] (modelled in the evaluation framework) consume significant power during reception; in the particular case of the CC2420 the power dissipation in Rx mode is slightly higher than the Tx mode. This becomes significant in contention based MACs in which the Rx mode is the dominant state. Therefore, the scheduled contention MAC (C-MAC) included in the base architecture XLCA adopts several known techniques to minimise the radio consumption and reduce the impact of congestion problems. Different radio interfaces used in sensor networks (e.g. the CC1000 [43]) tend to dissipate maximum power in transmit mode; however minimising *idle listening* is always a requisite in WSN.

The alternation of sleep and wake periods in the power management of C-MAC represents the main energy saving. During the wake period, the channel is shared amongst neighbours to carry out the data transmissions by using Carrier Sense Multiple Access (CSMA), random backoffs and an IEEE 802.11 like four-way handshaking mechanism (RTS/CTS/DATA/ACK). *Aggregation* is done to enable multiple data packet transmission during the RCDA (RTS-CTS-*n*DATA-*n*ACK) exchange, reserving with the RTS/CTS the required time duration. One ACK is sent after every DATA packet in order to avoid packet loss if a collision occurs. Indeed, because of the build up of traffic close to the sink (the funnelling effect introduced in Section 1.4.1), loss of aggregated data packets is more likely if these are sent as a burst; thus the extra ACK packets overhead is justified. With small duty-cycles, *Aggregation* achieves higher throughput and smaller delays.

In addition to the routing function of the MAC control packets previously explained, the RTS/CTS also avoids collisions informing neighbour nodes of the imminent data transmission. A Network Allocation Vector (NAV) technique enables a reduction of the energy consumption by putting nodes in an idle state to defer the channel access for the duration of the ongoing transmission. In addition, an Automatic Repeat Request (ARQ) retransmission scheme is also implemented to avoid data losses. Figure 4.4 shows the time diagram of C-MAC operation.

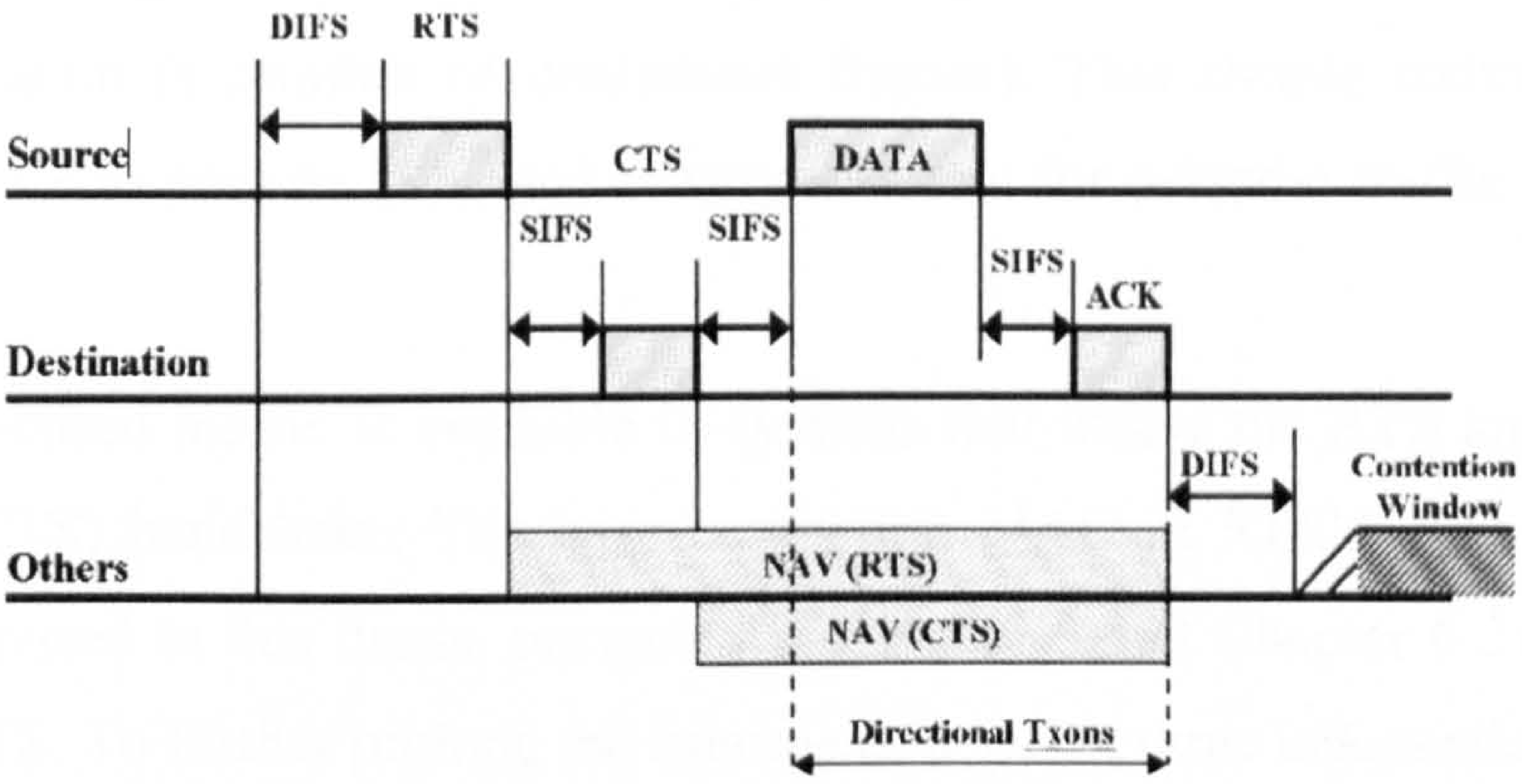


Figure 4.4 - Time diagram of C-MAC operation (IEEE 802.11), where:

- *DIFS, Distributed inter-frame space = 350μs (Medium must be clear before send the packet).*
- *SIFS, Short inter-frame space = 100μs (Transition time between Rx and Tx states).*
- *RTS, CTS, ACK= 80bits / 250kbps = 32μs*
- *DATA = 320bits / 250kbps = 128μs*

4.1.5 Adaptive Schemes: Post-Deployment Requirements

Besides the specific adaptive schemes within the hybrid MAC SSAS and the proactive cross-layer schemes that will be described in Chapter 6 and Chapter 7 respectively, XLCA includes two default node-initiated adaptive mechanisms, one for node failure management and another for duty-cycle adjustment.

4.1.5.1 Baseline Failure Management: Reactive Rerouting

A baseline solution for failure management has been defined in XLCA based on reactive rerouting. Failure detection is carried out at the MAC layer by exploiting overhearing, while recovery consists of selecting a new parent node (next-hop). A neighbour node is deemed as dead if it does not reply to a number of consecutive Request To Send (RTS) messages sent to it or it has not been heard for a predefined period. A threshold is set at the Routing-MAC layer (*maxRTS*) to determine when the current parent node has become unavailable and should be disabled from the routing table. A rerouting is then triggered at the sender of a failed node to select the next node in the routing table as its next-hop neighbour. In subsequent frames the disabled neighbour will be reactivated in the Neighbour table (Figure 4.2) if it is overheard.

However, the neighbour is removed from the Neighbour table if it is not heard for a defined duration (a number of continuous frames). This simple technique avoids flooding of Hello packets [87], and is very efficient for periodic traffic applications [86].

The RTS-based metric is available in systems that utilise the RTS and The Clear To Send (CTS) handshake. The base contention MAC in XLCA and other MAC solutions devised in this thesis, presented in Chapter 5 and Chapter 6 , make use of RTS and CTS. To further prolong the lifetime of a WSN, three independent proactive solutions are presented in Chapter 7 .

4.1.5.2 Adaptive Sleeping

A training period (a number of consecutive frames) is set previous to any adaptation to the initial design parameters can be done. This training period is designed to allow the traffic patterns to become steady; usually between 5 to 10 times the inter-arrival packet is sufficient.

An *Adaptive Sleeping* mechanism considerably increases the network life avoiding energy waste in nodes that do not need to be awake during the whole active period. For example nodes located at the edges that have no neighbours further away can go to sleep once they have transmitted their data packets (line 2 in Figure 4.5a). Additionally, after the start of the network operation and once the traffic patterns become steady (training period C1), nodes that have received the expected number of packets (C3), measured and updated during previous frames, can schedule a timeout (Figure 4.5b): if during this time the node is not contacted by other neighbours it goes to sleep mode until the next frame. Whenever the traffic conditions change, the *Adaptive Sleeping* updates the expected traffic and thus adapts the duty-cycle to the new traffic conditions.

Adaptive Sleeping implementation (MAC Layer)

```
a) Start Active Time
  if ( currentFrame > trainingFrames ) //$C_1$
     if ( No Pkts to Send)
        if ( No Further Neighbours || Im Not Next Hop )//$C_2$
           GoToSleep()
        else
           schedule ( 3·timeout/hop2sink, sleep )
b) After Reception of ACK (DATA SENT)
  if ( $C_1$ & No Pkts to Send )
     if ( $C_2$ )
        GoToSleep()
     else if ( RX-PKTS ≥ AVG-PKTS ) //$C_3$
        schedule ( timeout/hop2sink, sleep )
     else
        schedule ( 3·timeout/hop2sink, sleep )

Note: timeout = 10% · ActiveTime
```

Figure 4.5 – The pseudo-code for the Adaptive Sleeping in C-MAC

Physical Layer and Channel Models

In the simulation of wireless networks, an adequate modelling of the physical layer (node's HW) and radio channel is essential for the proper assessment of the radio communications and associated power consumption.

An abstracted PHY model must provide the power profile of each node in the network, that is, the power consumption in each operation mode. Hence it is important to identify the major components that consume most of the power and determine the different operation modes.

As explained in 1.4.2 and shown in experimental tests [47][48][49], the radio channel in sensor networks exhibits unpredictable behaviours, not easily captured by simple propagation models. Additionally the channel environment varies dramatically among different application scenarios and decisions on the channel modelling are especially difficult for WSNs. Although this work takes into consideration empirical measurements in the modelling of the radio channel, the model is constrained to the real deployment conditions. Regardless the variations of the effective range in different environments, this work sets priority in the modelling of a rational interference channel that takes into account the implications of several simultaneous transmissions in a contention network. In the type of application topologies considered (see Figure 4.1) the main reasons for packets losses are interference among two or more colliding transmissions. The communications protocols proposed in this thesis attempt to decrease the impact of such interference problems, capturing them is essential for the co-design methodology.

4.1.6 Hardware Modelling

The hardware parameters are extracted from the WSN platform Tmote [88] which mounts the IEEE 802.15.4 compliant CC2420 radio transceiver [43]. Several reasons motivated the selection of Tmotes, and particularly the transceiver CC2420:

- 10 Tmotes were available for testing and this platform was used by other partners in the DIAS project. In addition it has the same radio transceiver than other well-known platforms (e.g. MicaZ [34] and TelosB [63]).
- The CC2420 has a good range performance in outdoor environments and it has the possibility to mount external antennas such as switched beam antennas (e.g. MAXBEAM [79]) that are modelled in Section 4.1.8.
- The CC2420 has lower transition times and higher data rate compared with other typical transceivers in WSN (e.g. CC1000 [43] mounted on Mica2[34]).

The aim of the hardware modelling is the assessment of the actual power used by different communications protocols inside the XLCA platform. In this sense it may be sufficient to consider the power consumed at the radio device of Tmotes. Moreover, the power consumption of the sensors (humidity, temperature and light) in the Tmotes are negligible [88], and the active power in the MSP430 microcontroller unit (MCU) is ten times smaller than this in the CC2420. However, the networking operations can actually demand an extensive use of the MCU and nodes with higher radio activity (traffic load) will require higher amount of operations at the MCU. To account the MCU usage, the approach here considers that the MCU and radio transceiver work together during the Tx and Rx states of the CC2420. With up to 16 million instructions per second (MIPS) at the MSP430 there is a wide budget of operations available to perform the XLCA protocols functionality.

In order to register the energy drain of every operation mode and transitions, a battery model has been considered and implemented in the XLCA simulator platform. In addition, directional antennas are considered in the solutions proposed in Chapters Chapter 5 , Chapter 6 and Chapter 7 , and the actual antenna model used is described here as a component part of the XLCA in the Section 4.1.8. For illustration purposes, Figure 4.6 shows the real components of the Tmote platform board and indicates the components that are considered in the Hardware modelling.

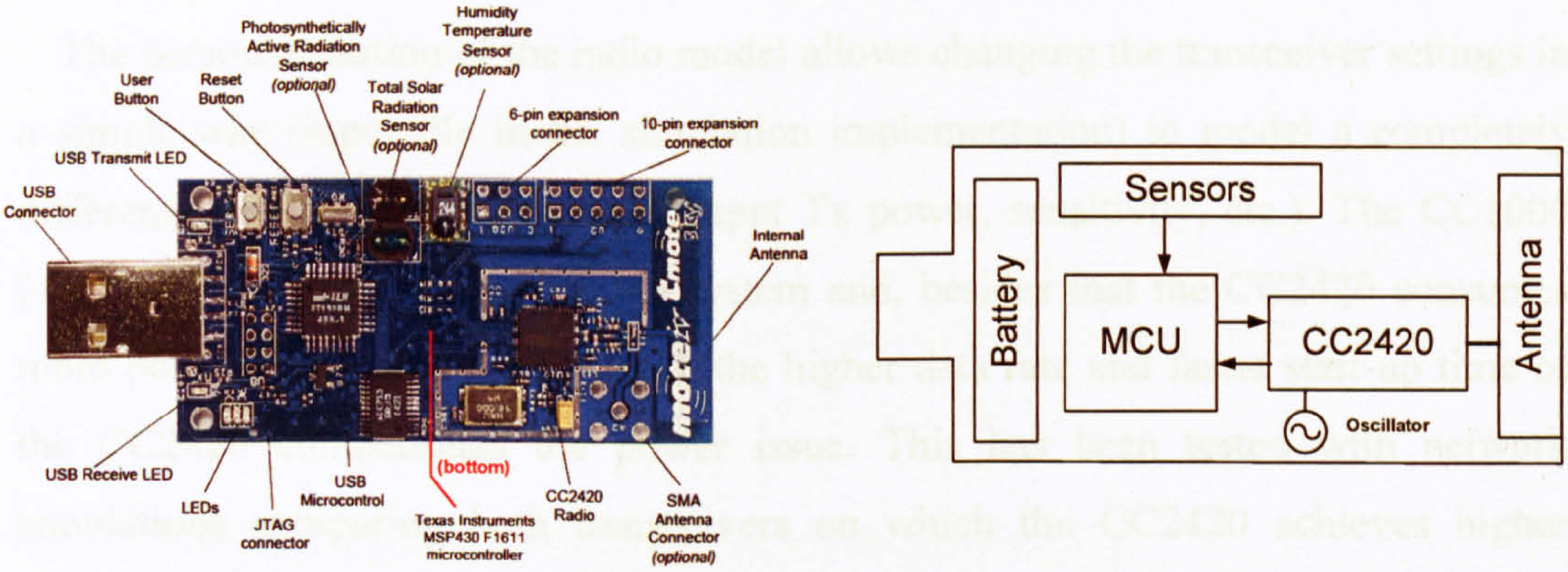


Figure 4.6 – Tmote components and practical modelling diagram

4.1.6.1 Radio Transceiver Model

Assuming the sensors power consumption to be negligible and that the Microcontroller (MCU) can run parallel to the Radio, here only four operation modes are considered [88]: SLEEP (Radio OFF, Oscillator OFF, MCU Sleep), IDLE (Radio Idle, Oscillator ON, MCU Sleep), Rx (Radio Rx, Oscillator ON, MCU ON) and Tx (Radio Tx, Oscillator ON, MCU ON). Associated power and transition times are shown at Figure 4.7. The CC2420 has eight programmable output Tx powers, from 0 to -25 dBm. The default power considered in the network simulation is the maximum one, 0dBm, and the associated Tx current consumption (plus 2.1mA of the MCU [88]) is represented in Figure 4.7.

An important drawback in most of current WSN devices is the high Start-up time required to wake up the Radio from Sleep mode, where the frequency synthesiser circuitry is the major responsible component. As the duration of a communication cycle RCDA is about 1.7ms, the 4ms start-up time at the CC2420 (Figure 4.7) constrains the chance to go sleep when waiting to access the channel (i.e. NAV scheduled), forcing the Radio to remain in the Idle state (Oscillator ON). Additionally the rest of transition states are not negligible and the switching time will have a significant impact on the network performance.

Another important consideration is the unusual relation between Tx and Rx current consumption at CC2420 (Tmotes). The high Rx power will cause important repercussions improving the network life due that during the active period, reception will be a dominant state in contention based MACs.

The parameterisation of the radio model allows changing the transceiver settings in a simple way (input file in the simulation implementation) to model a completely different radio (power, frequency, output Tx power, sensitivity, etc.). The CC1000 [43] has been also modelled in the system and, besides that the CC2420 consumes more power in Rx than the CC1000, the higher data rate and faster start-up time of the CC2420 compensates the power issue. This has been tested with network simulations comparing both transceivers on which the CC2420 achieves higher performance in terms of energy-efficiency when the assumed range is the same.

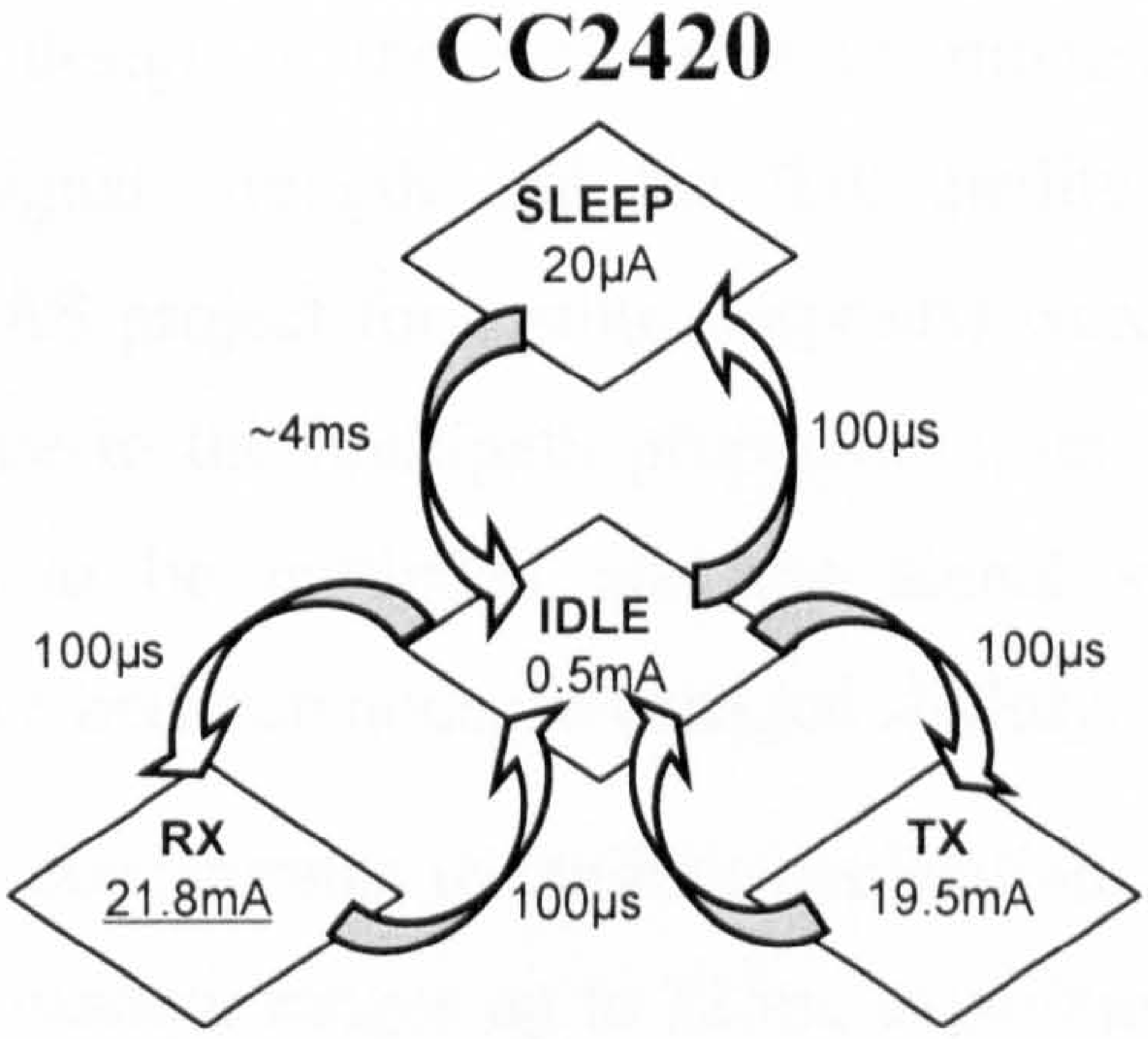


Figure 4.7 - Operation states and transitions

4.1.6.2 Battery Module

In order to compare network and node's lifetime with different communications protocols and antenna configurations (OD, directional), a battery model has been incorporated. Due to battery chemistry, voltage and current levels vary depending on how the energy is extracted from a battery [89], in addition of the environmental conditions. Although it may not reflect the real battery discharge behaviour, this work considers sufficient the use of a linear battery model for comparison purposes.

The battery level in a sensor node k starts with a fixed value $B_k(0)$ at time 0, expressed in miliamperes (mA) per second. The remaining battery capacity at time t is:

$$B_k(t) = B_k(0) - \int_0^t I_k(\tau)d\tau \qquad (1)$$

where $I_k(\tau)$ is the total current consumed at node k at time τ obtained as the sum of the instantaneous current consumption of the different states (Figure 4.7) multiplied by the time spent at each state:

$$I_k = (I_{tx} \cdot t_{tx}) + (I_{rx} \cdot t_{rx}) + (I_{idle} \cdot t_{idle}) + (I_{sleep} \cdot t_{sleep}) + (I_{switch} \cdot t_{switch}) \qquad (2)$$

Note that during the switching time, the mean current value between the transition states is assumed.

4.1.7 Radio Channel and Interference Modelling

4.1.7.1 Experimental results with Tmotes and Various Antennas

Previous to the final design of the radio channel model, several experimental measurements of the signal strength and the link quality indicator on Tmotes (available within the DIAS project for testing purposes) were made in outdoor and indoor environments. Due to the multipath propagation, an indoor environment in WSN is very difficult to be modelled and the signal strength presents high fluctuations when distance between nodes is changed slightly.

In any case, this work concentrates in outdoor applications. Although the Tmotes datasheet prognosticates outdoor ranges up to 125m, experiments with nodes located at 1m height in an open space lawn never managed more than 90m range with the default internal printed antenna (PCB Inverted-F microstrip) on Tmotes [88]. In addition, at ranges higher than 70-80m, the packet drops were significantly increased. Moreover the antenna polarisation on Tmotes has an important influence in the effective gain, and as a result the antenna radiation pattern has deep gain shadows in certain directions. However ranges up to 140m where possible with the substitution of one of the pair of nodes antennas with a monopole OD antenna or a directional antenna with higher gain that this in the internal antenna.

With the assumption that the Tmotes modelled have the default internal OD antenna, the parameters of the channel model have been considered to allow a maximum outdoor range of around 80m. Higher range can be accounted when switched beam antennas are in place. These antennas are modelled in Section 4.1.8.

4.1.7.2 The Radio Channel Model

Some of the assumptions implicit in the simulations do not necessarily reflect real-world conditions. Most important mistaken axioms simulating the Wireless Channel are described by Kotz's [90] from where it is possible to identify the next ones in this simulation framework:

- The world is flat.
- A radio's transmission area is circular (Omnidirectional antennas)
- All radios have equal range.
- Signal strength is a simple function of distance. (Plus Gain of antennas and transmission power considerations).
- There are no obstacles in the radio propagation channel.

The radio channel cannot be considered deterministic; signal propagation fading effects such as reflection or multipath in addition to parameters such as frequency, antenna orientation, variation of transceiver, battery voltage or environmental dynamics have a significant impact in the radio signal strength, as have been investigated in [91]. This thesis assumes an outdoor environment where nodes are stationary and within line of sight. In order to evaluate the impact of directional antennas in this environment it is considered sufficient and general approach to adopt the Friis' path loss model [92] adding an extra variable (X^{σ}) to account for the random signal deterioration (shadow fading). The received power at a distance d is calculated as,

$$P_r = \frac{P_t \cdot G_t \cdot G_r}{d^{\alpha}} \left(\frac{\lambda}{4\pi} \right)^2 \cdot X^{\sigma} \qquad (3)$$

Where X^{σ} is a log-normal random variable modelled as a zero-mean Gaussian function with standard deviation σ. A value of σ equal to 1dB is assumed here for the outdoor environment although tuning using empirical measurements will be required in order to reflect the actual scenario being modelled. The rest of parameters are: λ, the signal wavelength, G_t and G_r transmitting and receiving gain respectively and P_t the transmitted power (watts). The path loss exponent α varies from 2 to 5 depending on the environment. Here it is assumed equal to 2.8 as it better fits the Tmotes' RSS curve and maximum range in a particular outdoor environment. The model considers the transceiver CC2420 using a single frequency channel in the 2.4GHz band with parameters that have been shown in Figure 4.7 and Table 4.1.

Table 4.1 - Physical and MAC Parameters.

Data rate	250 kbps
Receiver Sensitivity	-94 dBm
Thermal Noise	-107 dBm
SNIR Threshold	5 dB
Maximum OD range	~80m
Data packet size	40 bytes
Control packet size	10 bytes
Buffer size (4kB):	100 packets
Frame Duration	20 sec
Random Backoffs	0.2 ↔ 4 ms
Initial Battery	3000mA/s

4.1.7.3 Interference Model

An accurate interference model is especially important in multi-hop networks where several simultaneous transmissions are likely to happen. In [93] different interference models are considered concluding that simplified interference models have significantly different results compared with the more realistic additive interference model. It is shown that published results comparing MACs and Routing strategies will have different conclusions adopting more realistic models. This thesis adopts the additive interference model as described in [93]. Basically during a packet reception time, every surrounding transmission is considered interference and its signal strength ((3)) is additively evaluated, in addition to thermal noise, for SINR (Signal to Interference-plus-Noise Ratio) calculation. If the SINR does not exceed a 5dB threshold a collision is assumed and the packet is discarded. The threshold value is adopted from experimental work in [94].

Finally, if the packet passes the threshold test and can be considered interference free, it is still possible to have bit error rates (BER) due to the demodulation/decoding effects. The BER is calculated depending on the modulation scheme and the SINR obtained, the value is extrapolated to the total size of the packet in order to obtain the Packet Error Rate (PER). Due to the big threshold assumed and the transceiver characteristics the PER results negligible.

Figure 4.8 exemplifies the occurrence of a Data packet collision (①→Sink), as a result of the adding up of two interference packets (RTS from ② and ACK from ②$_2$), the SNIR minimum threshold set for correct packet demodulation. It should be noted that the two-hop nodes ② and ②$_2$ are not in range of the sink, however their transmissions are captured in the interference model.

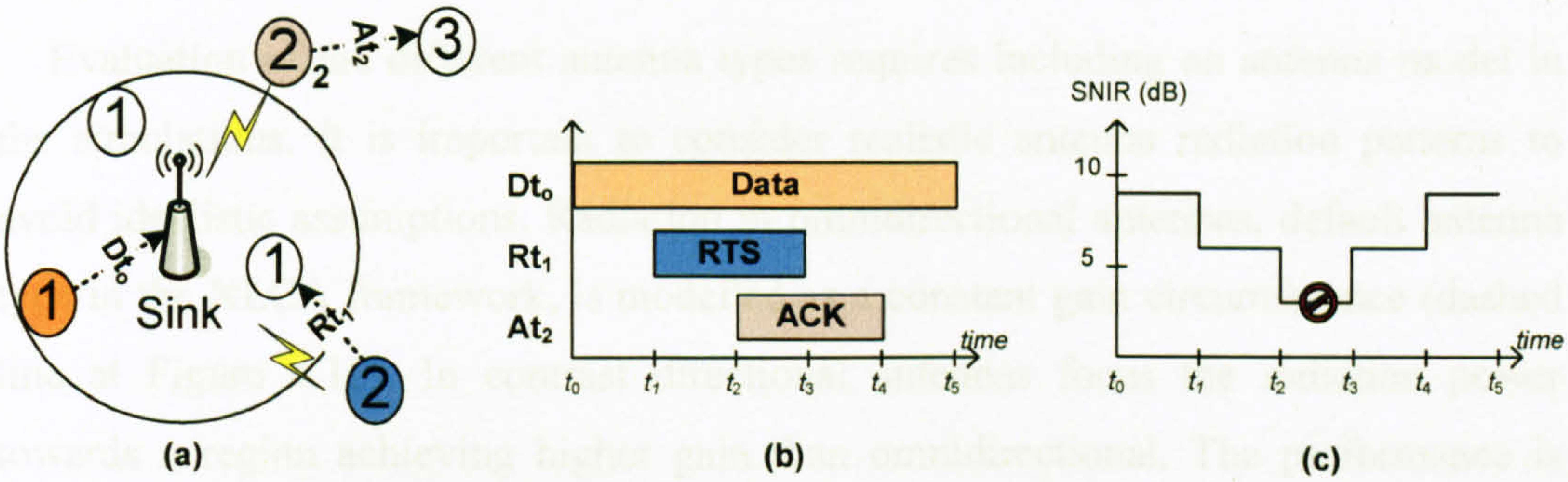


Figure 4.8 – Additive Interference Model: Occurrence of Data Packet Lost

4.1.8 Directional Switched Beam Antenna Modelling

Among the various directional technologies, the switched beam antenna (SBA) is a small-size/low-cost suitable solution for sensor networks. In particular, SBAs using inexpensive off-the-shelf components at license-free frequencies such as 2.4GHz or 5GHz are very attractive. Figure 4.9 shows a MaxBeam [79] switched beam antenna of 4 elements that have been tested in Tmotes [88] generating up to 15 beams plus an omnidirectional mode, which is the sum of all radiating beams. The antenna control is very simple and does not consume power, it is performed triggering the state of the 4 digital pins (OD mode is equivalent to the 4 pins set high).

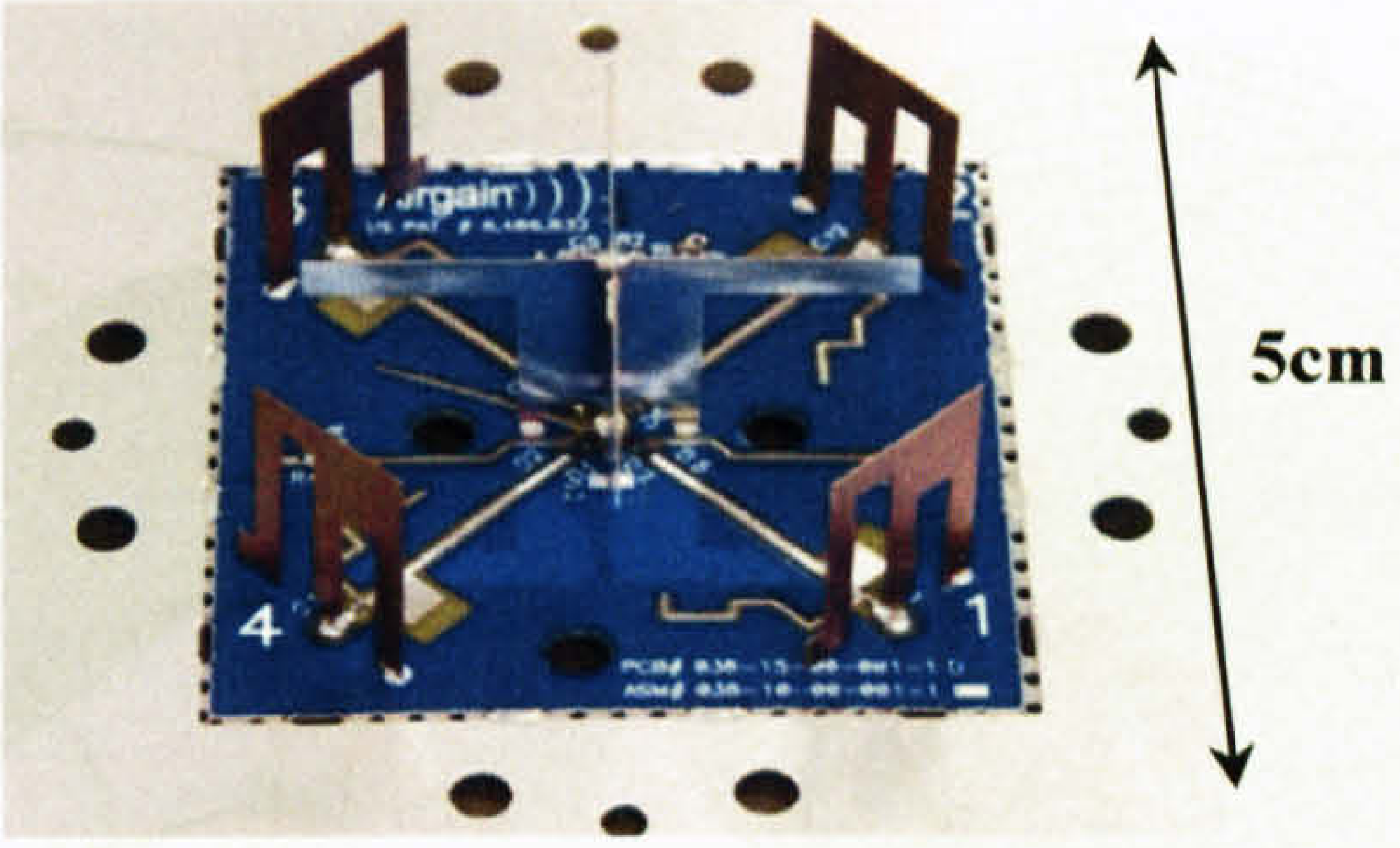
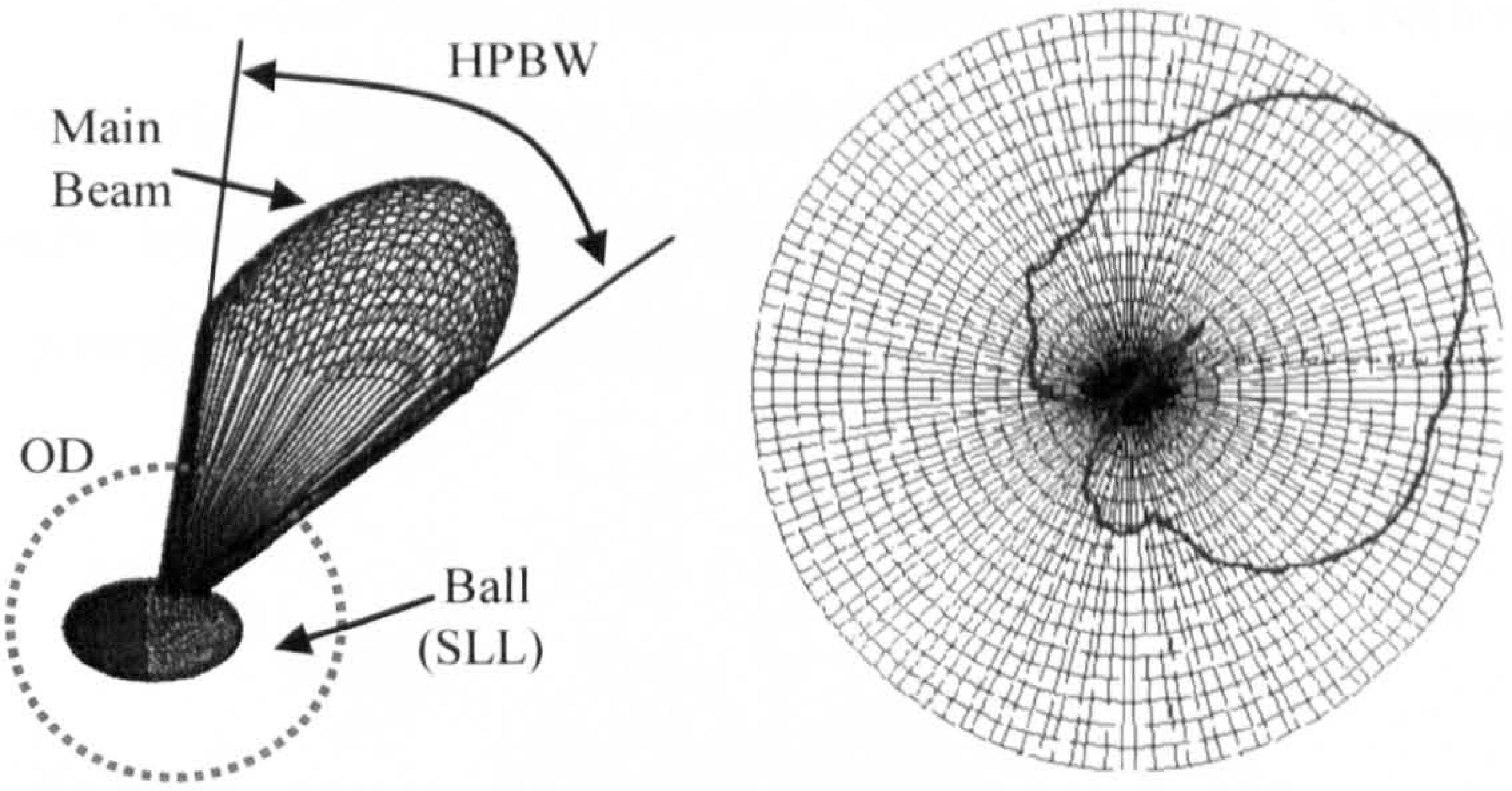


Figure 4.9 – Four element switched beam antenna (2.4GHz ISM band)

The directional solutions proposed in this work assume this type of switched beam antennas that are modelled in this section. The number of switched beams (sectors) of the SBA considered in this thesis ranges between 2 and 8. In the SBA modelled to types of operation is possible, directional with one beam selected, and omnidirectional (overlap of all beams' radiation).

Evaluation of the different antenna types requires including an antenna model in the simulations. It is important to consider realistic antenna radiation patterns to avoid idealistic assumptions. Radiation in omnidirectional antennas, default antenna type in the XLCA framework, is modelled as a constant gain circumference (dashed line at Figure 4.10). In contrast directional antennas focus the radiation power towards a region achieving higher gain than omnidirectional. The performance is quantified by the directivity of the main beam, i.e. its beamwidth, usually specified between half power points, half-power beamwidth (HPBW), Figure 4.10(a).

However, modelling practical directional antennas is more complex and requires a consideration of real radiation patterns. Figure 4.10(b) shows the radiation pattern of a main beam in the MaxBeam switched beam antenna (Figure 4.9). Generally, simplistic antenna models are found in wireless proposals using directional transmissions. Related work in WSN suppose a Flat-Top model assuming same gain inside beamwidth and negligible power radiated in side lobes, which is very unrealistic.



(a) (b)

Figure 4.10 - Approximate (a) and practical models (b)

Here it is considered more appropriate the beam and ball model (Figure 4.10(a)) in order to model the switched beam antennas. The model represents the main beam of a switched beam antenna with non-uniform gain within the beamwidth and a constant level (ball) for account the sidelobes effect (SLL), (-12dB under Peak gain is assumed). The model is concerned only with the azimuth plane for antenna orientation and radiation pattern in this work.

The gain of the antenna in directional Tx or Rx mode is calculated in Equation 4 as a Gaussian function of the angle between the Peak gain axis and the direction towards the Rx or Tx respectively, see detail in Figure 4.11. A Gaussian shape ensures that each beam's gain varies from the maximum G_{max} (at θ_m) to the minimum $G_{min}= G_{max}/2$ at the borders of the beamwidth according to the HPBW definition, first formula of Equation 4

$$G_{t/r}(\theta_k)=\left|\begin{array}{l} G_{\max}\cdot e^{-\frac{(\theta_k-\theta_m)^2}{2\sigma_1^2}} \rightarrow \left|\theta_k-\theta_m\right| \leq \frac{HPBW}{2} \\ \frac{G_{\max}}{2}\cdot e^{-\frac{(\theta_k-\theta_m)^2}{2\sigma_2^2}} \rightarrow \frac{HPBW}{2} < \left|\theta_k-\theta_m\right| \leq \frac{3\cdot HPBW}{4} \\ SLL = G_{\max}\cdot 10^{\frac{-12}{10}} \rightarrow \left|\theta_k-\theta_m\right| > \frac{3\cdot HPBW}{4} \end{array}\right.$$

(4). However, using only this Gaussian the beam-ball model leaves a significant gap (9dB) between G_{min} and the side lobes level. In order to avoid this gap and further approximate the practical radiation pattern (Figure 4.10(b)) the model implemented in this work introduces a second Gaussian function between each side of the main beam and the side lobe level. The result is a continuous shape represented in Figure 4.11 and described in the following equation:

$$G_{t/r}(\theta_k) = \left| \begin{array}{ll} G_{\max} \cdot e^{-\frac{(\theta_k-\theta_m)^2}{2\sigma_1^2}} & \rightarrow \left|\theta_k-\theta_m\right| \leq \frac{HPBW}{2} \\ \frac{G_{\max}}{2} \cdot e^{-\frac{(\theta_k-\theta_m)^2}{2\sigma_2^2}} & \rightarrow \frac{HPBW}{2} < \left|\theta_k-\theta_m\right| \leq \frac{3\cdot HPBW}{4} \\ SLL = G_{\max} \cdot 10^{\frac{-12}{10}} & \rightarrow \left|\theta_k-\theta_m\right| > \frac{3\cdot HPBW}{4} \end{array} \right. \qquad \textbf{(4)}$$

$$\text{Where } \left\{ \sigma_1 = \frac{HPBW/2}{\sqrt{2\ln 2}} \ \& \ \sigma_2 = \frac{HPBW/4}{\sqrt{-2\ln(2\cdot SLL)}} \right\}$$

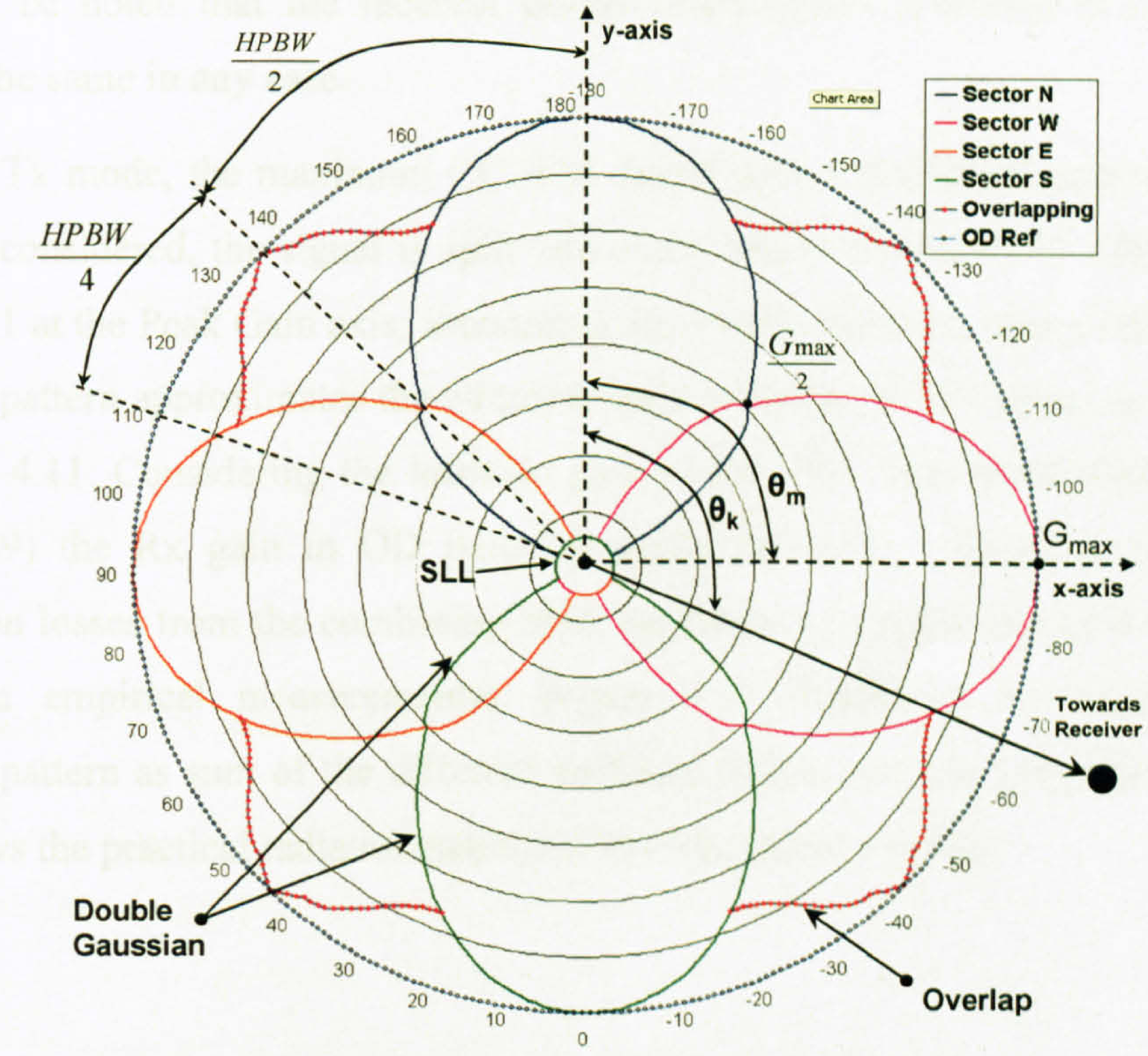


Figure 4.11 - Switched Beam Antenna Model

It is assumed that a switched beam antenna can generate a fixed number of beams in different fixed directions, where each beam covers one "sector" of the total 360^{o} coverage and the first sector is always pointing to the y-axis (North). Increasing antenna directionality requires a higher number of beams (sectors) with smaller beamwidth and higher gain. This model supposes a normalized maximum gain equal to the number of sectors. For example, in Figure 4.11 a switched beam antenna of 4 sectors generates 4 beams of $HPBW = 360^{o}/4 = 90^{o}$ and $G_{max}= 4$. This gain achieves, for instance, 1.64 times more range (3) than OD $G_t=1$.

In the directional mode, Tx and Rx are done selecting one of the available beams, eventually the one pointing closer to the Rx/Tx node respectively (beam gain $G_{t/r}(\theta_k)$ is calculated using Equation 4. The beam selection is presumed to be carried out at the initialisation. The MAC design may require reducing Tx power in directional mode with the intention of reducing range and power consumption. For instance, if the power P_t is reduced by the number of sectors (G_{max}), the directional mode results in the same effective Tx gain ($P_t{\cdot}G_t=1$), thus the range, than OD antennas. However it should be noted that the receiver power consumption specified in Figure 4.7 remains the same in any case.

In OD Tx mode, the maximum CC2420 output power (0dBm) is selected and, if SBA are considered, the signal is split into every beam, therefore the effective gain ($P_t{\cdot}G_t$) is 1 at the Peak Gain axis; accounting the overlap between beams the resultant radiation pattern approximates the circumference radiation of OD antennas as shown in Figure 4.11. Considering the intrinsic gain of the SBA directional elements (see Figure 4.9) the Rx gain in OD mode is equal to $G_r(\theta_k)$ (Equation 4) minus attenuation losses from the combining SBA hardware (-1.5dB is assumed here from MaxBeam empirical measurements). Figure 4.11 illustrates the resultant OD radiation pattern as sum of the different switched beams and for comparison Figure 4.12 shows the practical radiation pattern of the MaxBeam antenna.

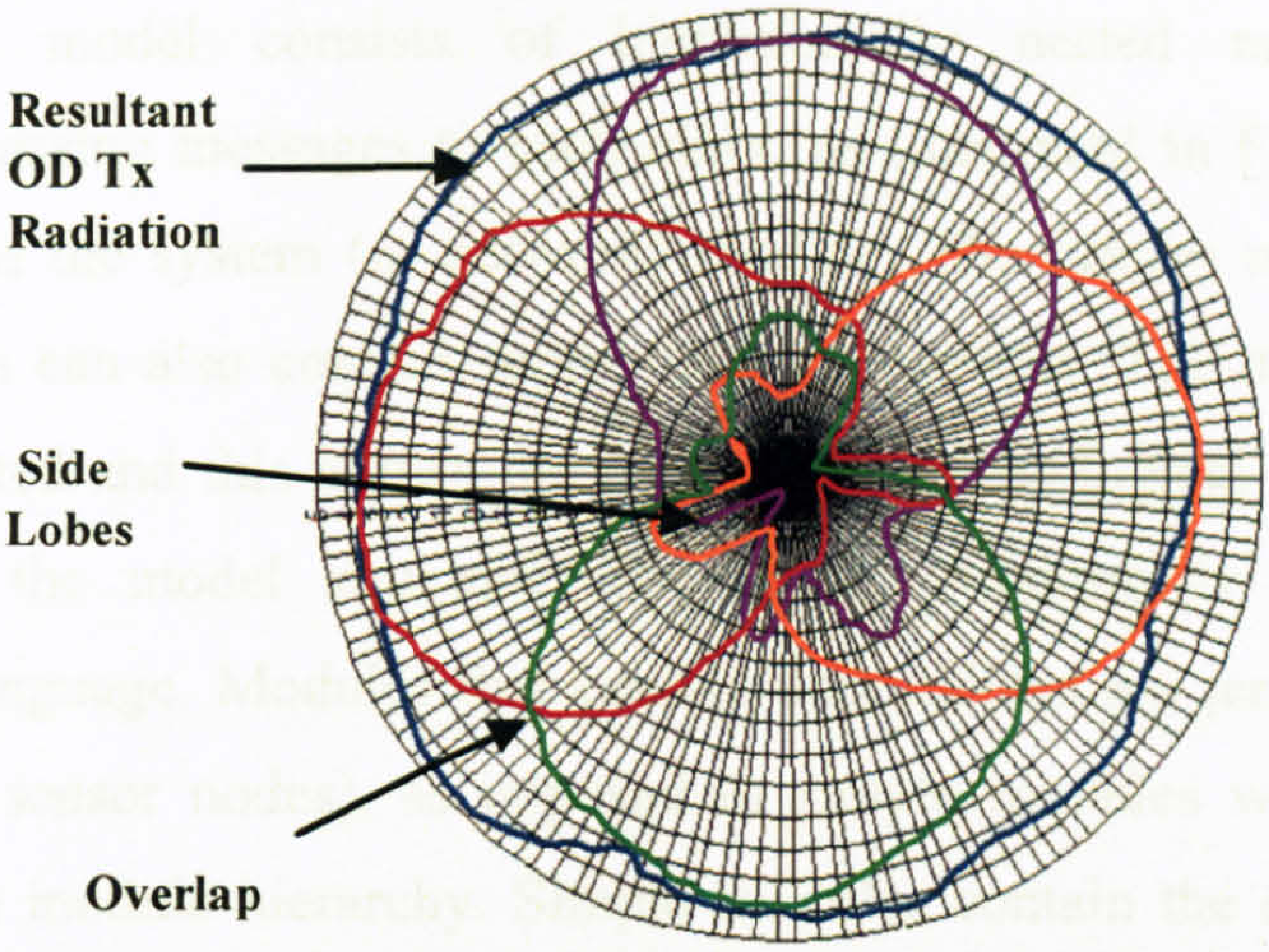


Figure 4.12 - Radiation pattern of a Real switched beam antenna (Figure 4.9)

4.2 Simulation Framework

The XLCA architecture is implemented in the simulator OMNeT++ [95] the main features of which are indicated in Section 4.2.1. The selection of OMNeT++ over other well-known network simulators such as ns-2 [96] is based in several advantages and features such as the higher flexibility of OMNeT++ in the simulation of network and hardware architectures, the ability to run large networks, the hierarchical module structure, the graphical debugging and tracing support and a good variety of models available (as those in the Mobility Framework [97]). This simulator is experienced increasing consideration for simulation in ad-hoc networks and there has been numerous works in WSN that have made use of it, such as SenSim [98], INET-Framework [99], PAWiS [100] and Merlin [101], among others. The framework is primarily focused on simulating inter and intra node communications.

4.2.1 OMNeT++ Simulator

OMNeT++ [95] (Objective Modular Network Testbed in C++) is a discrete event, component based, general purpose, public source, modular simulation framework written in C++. It provides a basic infrastructure wherein modules exchange messages. It runs on Windows and Unix platforms and offers a command line interface as well as a powerful graphical user interface (GUI) support for animation and debugging.

An OMNeT++ model consists of hierarchically nested modules, which communicate by passing messages to each other, as illustrated in Figure 4.13. The top level module is the system (or network) module. The system module contains submodules, which can also contain submodules themselves. The depth of module nesting is not limited and this allows the user to reflect the logical structure of the actual system in the model structure. The model structure is described with OMNeT's NED language. Modules that contain submodules are termed compound modules (e.g. the sensor nodes), as opposed to simple modules which are at the lowest level of the module hierarchy. Simple modules contain the algorithms (e.g. the sensor node functionality) in the model; these are written in C++ using the OMNeT++ simulation class library. An OMNeT++ model physically consists of the following parts:

- NED language topology description(s).
- Message definitions.
- Simple modules implementations in C++ code.

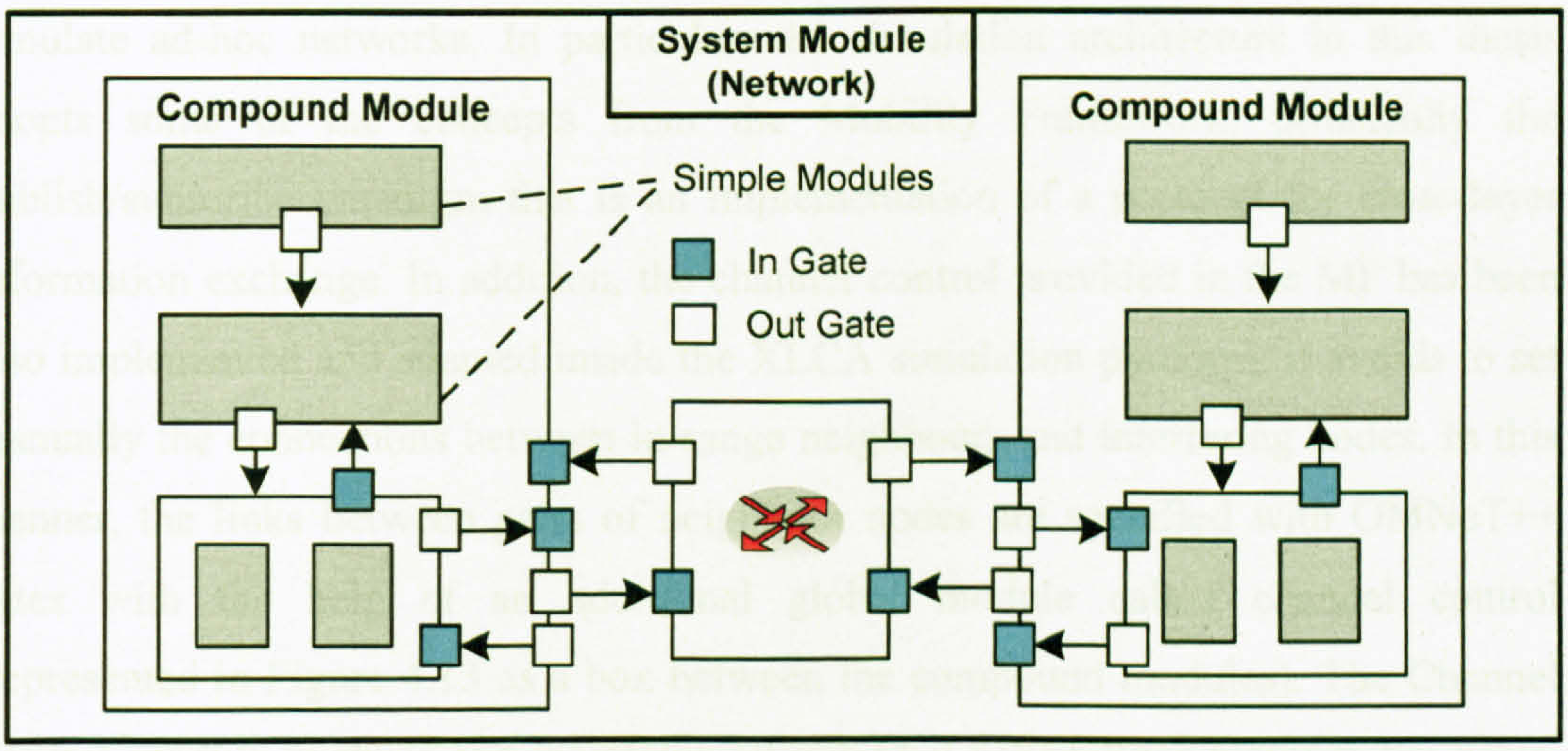


Figure 4.13 – OMNeT++ module hierarchy

The modules communicate by exchanging messages that can be classified as been either network or self messages. Network messages are analogous to their real world counterparts and can be used to represent the exchange of air-frames between nodes or packets between layers (Application-Routing-MAC) inside the nodes protocol stack. The term self message is given to messages that are sent from and received at the same simple module (self-messages are commonly used to implement timers). In the event-simulator OMNeT++, the local simulation time of a module advances when the module receives a message (network or self-message).

Gates are the input and output interfaces of modules; OMNeT++ supports only simplex (one-directional) connections, so there are input and output gates. Messages are sent out through output gates and arrive through input gates (as illustrated in Figure 4.12).

The modules are compiled and linked with the simulation kernel, and result in the simulation application. OMNeT++ offers a GUI-based frontend which enables visual debugging of the communication processes of the model on a per-event basis at simulation runtime. An optional command line-based frontend can be utilized for increased simulation performance.

4.2.1.1 Mobility Framework

The mobility framework (MF) [97] for OMNeT++ is a specific purpose add-on to simulate ad-hoc networks. In particular, the simulation architecture in this thesis adopts some of the concepts from the Mobility Framework, principally the publish/subscribe paradigm that is an implementation of a protocol for cross-layer information exchange. In addition, the channel control provided in the MF has been also implemented and adapted inside the XLCA simulation platform; it avoids to set manually the connections between in-range neighbours and interfering nodes. In this manner, the links between pairs of neighbour nodes are specified with OMNeT++ gates with the help of an additional global module called channel control (represented in Figure 4.13 as a box between the compound modules). The Channel Control module controls and maintains all potential connections between the hosts. An OMNeT++ connection link in the MF does not automatically indicate that the corresponding hosts are able to exchange data and communicate with each other. The ChannelControl module only connects all hosts that possibly interfere with each other (in accordance with the additive interference model).

4.2.2 Integration of Modules in OMNeT++

After developing models for each component (layers), it is crucial to integrate them together to provide the intra-node functionality and inter-node communications, also to link the total power consumption to the design parameters of these components. The XLCA functionality and models that have been described in 4.1 have been implemented inside the OMNeT++ simulator resulting in the XLCA simulation framework. In this framework, the system has one top-level network compound module (called *sim*). The network module represents the whole sensor network and contains sensor nodes (*host*) compound modules. The practical representation of the *sim* and *hosts* modules has been shown in Figure 4.1, which can be characterised using the OMNeT++ modules (Figure 4.13). The *sim* module is responsible for setting up the network topology and the individual sensor nodes modules. The host modules include application, Routing-MAC, and Physical layer modules. Modules for different layers within a node exchange messages directly with modules for adjacent layers. Neighbouring nodes exchange messages directly via the physical layer modules.

This integration procedure can be made relatively independent of the actual designs used for the components. As in the integration of software components, the interface of every model needs to be decided first in this integration process. Thereafter the functionality of the simple modules (e.g. Routing and MAC algorithms) can be changed simply by direct substitution of the C++ code associated with the simple modules. Once the interfaces are determined, the interactions between the models can be studied running the simulations. For example, the total power consumption can be evaluated from the design parameters.

The Figure 4.14 shows the implementation of the different modules in the XLCA simulation framework:

- *appl* – Application layer, responsible for the generation of application data packets (4.1.1).
- *net* – Network layer, it can be used to implement point-to-point routing mechanisms (e.g. AODV [102], however in the current implementation it

only forwards the data packets from the application layer down to the MAC (*nic*) layer.

- The *nic* (network interfaces) module is responsible for the inter-node communications. It is compounded by:
  - the radio modules: *radio* transceiver (modelled in 4.1.6.1) and *antenna* (which gain is modelled with the Equation 4 in 4.1.8),
  - the physical layer modules: channel model (*snreval*, calculates the channel path loss of the incoming signals with (3) in 4.1.7.2) and *decider* (additive interference model in 4.1.7.3) and,
  - MAC (*mac*) layer module that includes the fusion Routing-MAC layer functions previously described:
    - Self-organising initialisation (4.1.2)
    - Next-Hop Routing (4.1.3)
    - Medium Access Control (4.1.4)
    - Adaptive Routing-MAC schemes 4.1.5)

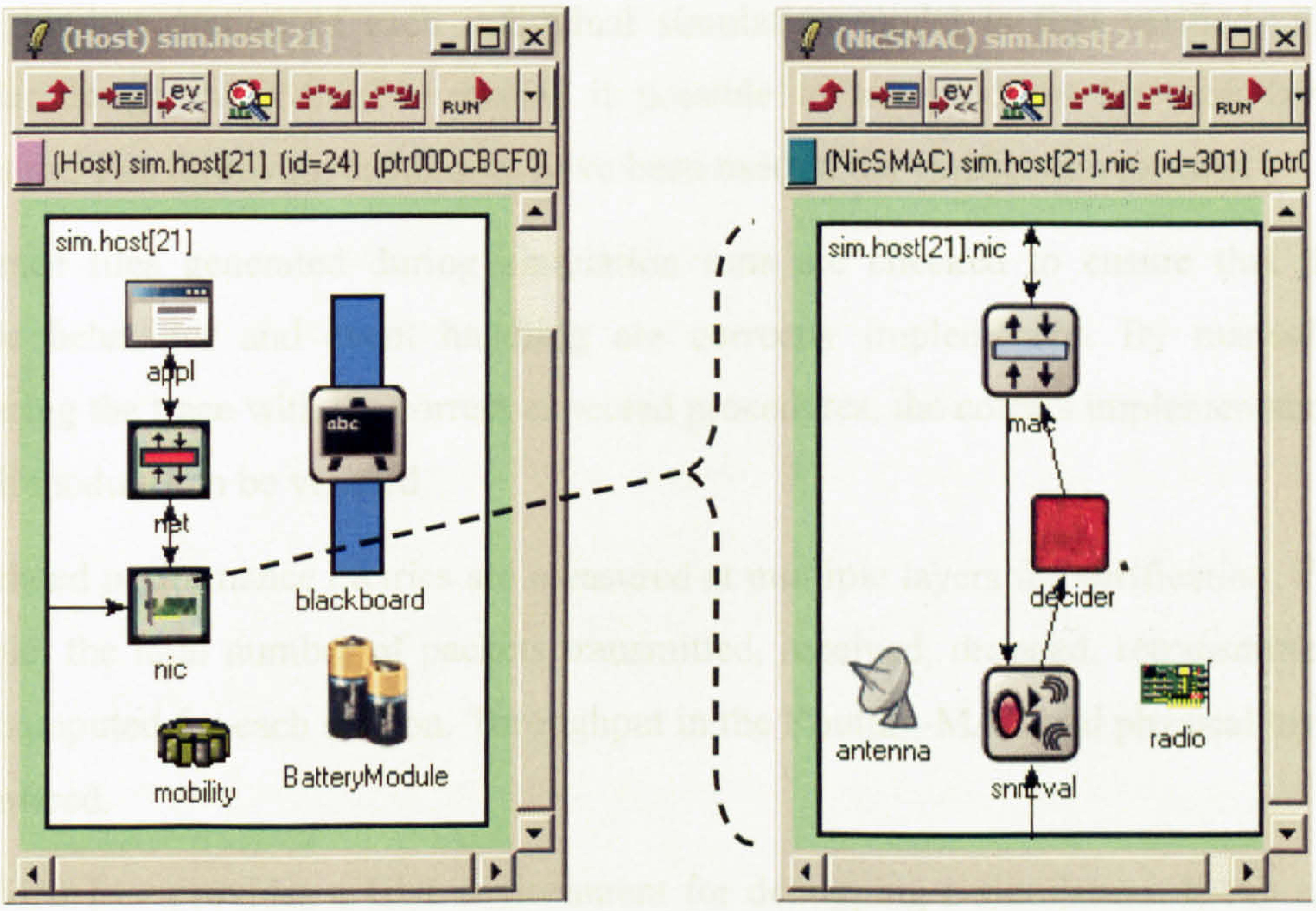


Figure 4.14 – Interlayer Structure: Integration of modules in OMNeT++

The XLCA simulation framework has involved an important effort in terms of time (>2 years) and lines of code (~13000). This framework includes the implementation of every module represented in Figure 4.13 with the functionality described in 4.1 and the solutions that are to be explained in Chapter 5, 6 and 7. In addition, a topology generator and various PHP files for post-processing of numerical and graphical results have been also implemented. The input parameters of every module and overall output statistics and metrics appear in Appendix A: Simulation Input and Output

4.2.3 Test-Bed Validation and Verification

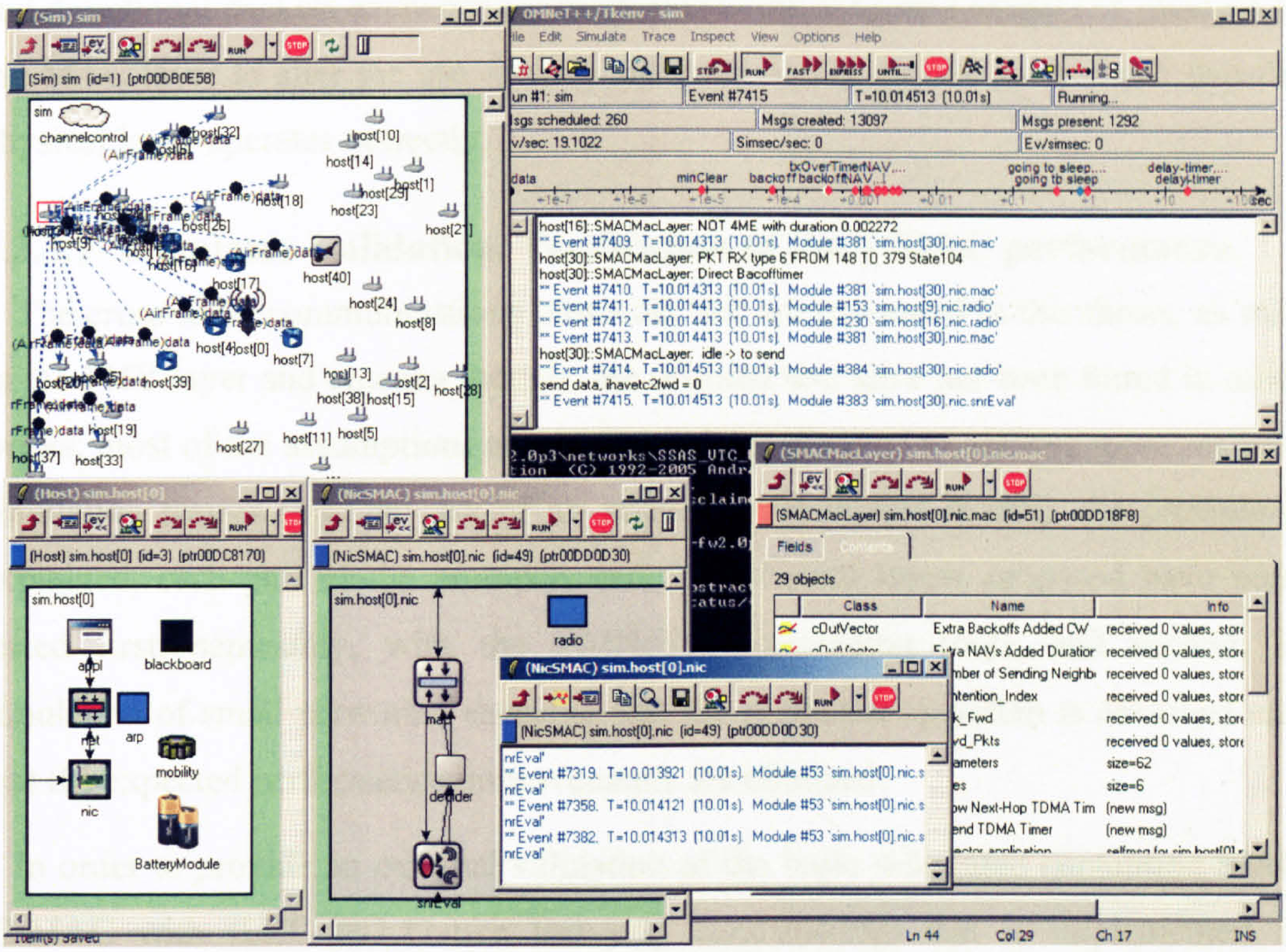
In OMNeT++, the graphical interface (see Figure 4.15) allows to probe every component and interaction with printing and messages during the simulation. In addition the complete collection of parameters which are available at the end of the kernel (command line) simulation also permits to identify the proper operation. For example, the battery level can be verified analytically accounting for the time that a particular node has spent at each state (Figure 4.7).

The implementation of each individual simulation model is first verified. The modular design in OMNeT++ makes it possible to test modules for each layer separately. The following techniques have been used in the verification process:

- Trace files generated during simulation runs are checked to ensure that the module behaviour and event handling are correctly implemented. By manually comparing the trace with the correct expected procedures, the correct implementation of each module can be verified.

- Related performance metrics are measured at multiple layers for verification. For example, the total number of packets transmitted, received, dropped, retransmitted, etc is computed for each session. Throughput in the Routing-MAC and physical layer is compared.

- OMNeT++ provides a GUI environment for debugging a simulation. It can run the simulation step-by-step, in batch mode, or advance to a specific simulation time. When a simulation is paused, the simulation status, future events, module messages, and statistics variables can be inspected (see Figure 4.15).



```
un #1: sim                Event #7415            T=10.014513 (10.01s)    Running...
sgs scheduled: 260        Msgs created: 13097                            Msgs present: 1292
v/sec: 19.1022            Simsec/sec: 0                                  Ev/simsec: 0
```

```
host[16]::SMACMacLayer: NOT 4ME with duration 0.002272
** Event #7409.  T=10.014313  (10.01s).  Module #381 `sim.host[30].nic.mac'
host[30]::SMACMacLayer: PKT RX type 6 FROM 148 TO 379 State104
host[30]::SMACMacLayer: Direct Bacofftimer
** Event #7410.  T=10.014313  (10.01s).  Module #381 `sim.host[30].nic.mac'
** Event #7411.  T=10.014413  (10.01s).  Module #153 `sim.host[9].nic.radio'
** Event #7412.  T=10.014413  (10.01s).  Module #230 `sim.host[16].nic.radio'
** Event #7413.  T=10.014413  (10.01s).  Module #381 `sim.host[30].nic.mac'
host[30]::SMACMacLayer:  idle -> to send
** Event #7414.  T=10.014513  (10.01s).  Module #384 `sim.host[30].nic.radio'
send data, ihavetc2fwd = 0
** Event #7415.  T=10.014513  (10.01s).  Module #383 `sim.host[30].nic.snrEval'
```

(NicSMAC) sim.host[0].nic (id=49) (ptr00DD0D30)

```
nrEval'
** Event #7319.  T=10.013921  (10.01s).  Module #53 `sim.host[0].nic.s
nrEval'
** Event #7358.  T=10.014121  (10.01s).  Module #53 `sim.host[0].nic.s
nrEval'
** Event #7382.  T=10.014313  (10.01s).  Module #53 `sim.host[0].nic.s
nrEval'
```

(SMACMacLayer) sim.host[0].nic.mac (id=51) (ptr00DD18F8)

29 objects

```
Class          Name                          Info
cOutVector     Extra Backoffs Added CW       received 0 values, store
               Extra NAVs Added Duratior     received 0 values, store
               mber of Sending Neighb        received 0 values, store
               ntention_Index                received 0 values, store
               k_Fwd                         received 0 values, store
               vd_Pkts                       received 0 values, store
               ameters                       size=62
               es                            size=6
               ow Next-Hop TDMA Tim          (new msg)
               end TDMA Timer                (new msg)
```

Figure 4.15 - Simulation Environment: GUI interface in OMNeT++

Therefore the GUI environment is very helpful in verifying the simulation models. After the verification of each module, the system module is tested with different network topology and traffic patterns using the above techniques.

The OMNeT GUI also enables the identification of problems, for example a node from which the sink is not receiving any packet because it is not interconnected with any neighbour. In addition it results very useful to check the post-deployment adaptability when at some known time instant these changes are expected. For example, the effect of the *Adaptive Sleeping* (4.1.5.2) after the training period or the Proactive Schemes (7.2.1) at the Vulnerable Checking Times (VCT) of the proactive schemes presented in Chapter 7 .

Due to the modular concept and hierarchy of the simulation framework, once the interfaces between the elements (e.g. MAC-PHY) have been established and verified, alteration of functionality of one of the elements needs only to be checked in the layer to which it applies. For example, once it has been checked with the OMNeT GUI that the path loss calculated with the gain of the SBA (Equation 4) during OD and directional packets exchanges corresponds to the proposed model (3), changes in the MAC layer to alter the use of such antennas do not require to re-check that the physical layer operates correctly.

4.2.3.1 Simulator Validation. Verification of the S-MAC performance.

The cross-layer communications protocols that are presented in this thesis, as well as the PHY layer and antenna models, are original and have not been found in other works; most of the assumptions adopted have been directed to achieve more realistic simulation results (e.g. the use of an additive interference model). As previously explained, each part of the protocols and the different layers proposed have been tested first, separately, with the OMNeT++ debugging tools, and second, in simulation of small networks, checking that the predicted operation is observed and that the expected performance improvements are obtained.

In order to provide an external validation of the basic scheduled contention MAC (S-MAC with IEEE 802.11-like four-way handshaking) that is implemented in XLCA, the same simulation scenario (grid) and PHY assumptions found in [44] have been repeated in the XLCA simulation framework obtaining very similar performance results of S-MAC. The simulation setup and parameters can be found in the section 4.1 of [44] for the nodes-to-sink communication scenario:

- 100 nodes in a 10 by 10 grid with radio range so that non-edge nodes all have 8 neighbours. Additive interference is not considered, and packets only collide if direct neighbours transmit at the same time.
- Energy consumption of 20μA while sleeping, 4mA while receiving and 10mA while transmitting.
- Unique packet size of 100 bytes.
- Inter-arrival packet times of 100 s, 50 s, 25 s, 16.6 s, 12.5 s and 10 s, which is equivalent to a data load of 1, 2, 4, 6, 8 and 10 bytes per node per second.
- The S-MAC protocol (duty-cycle) is tuned to provide at least 90% of throughput. An adaptive sleeping scheme is not considered.

The simulations results with XLCA and these assumptions are shown in Figure 4.16 where the average battery used per node (mA) is plotted for the different data rates. The results obtained in this simple scenario match those that are presented in Figure 8 of [44].

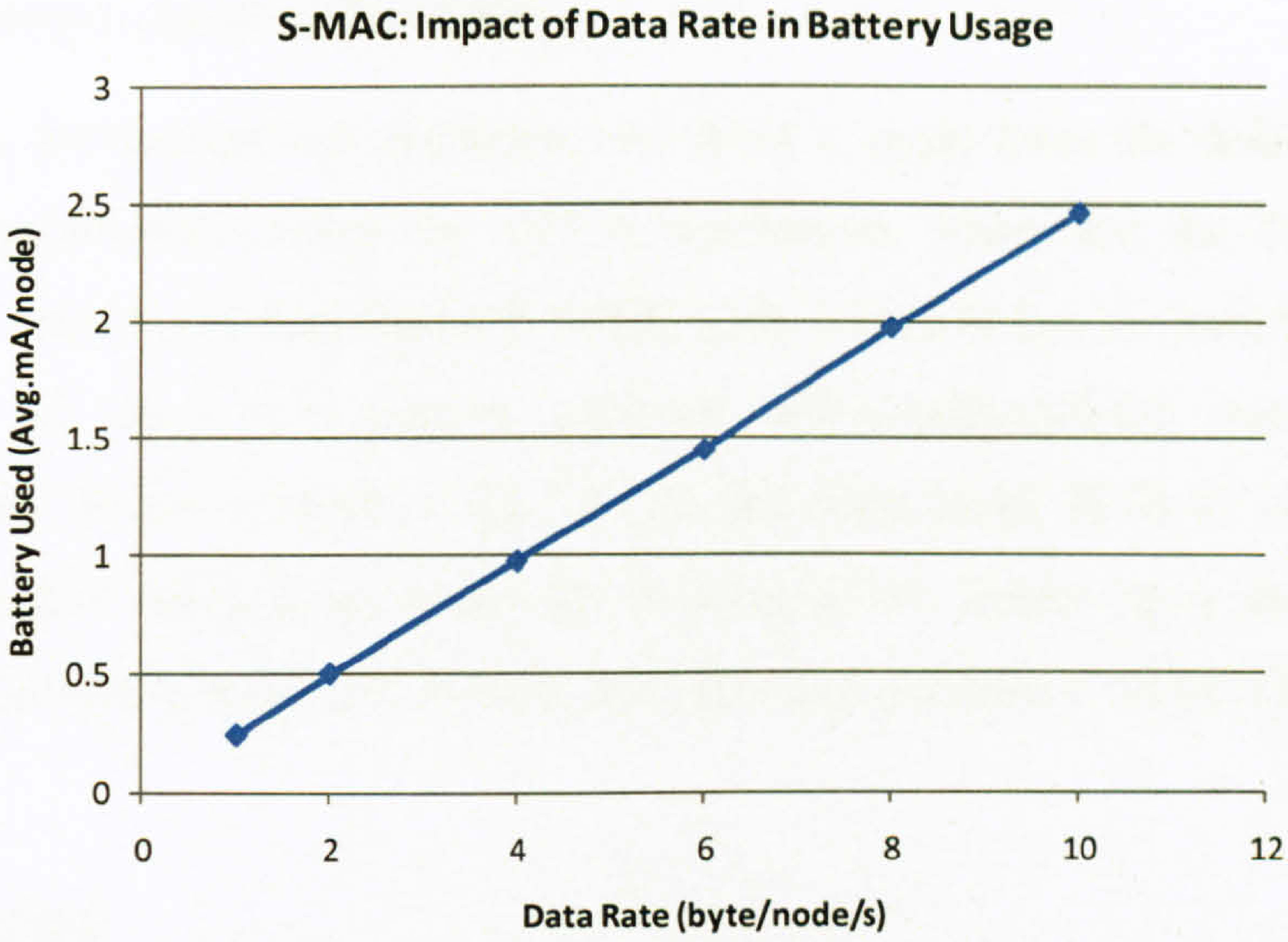


Figure 4.16 – Average battery used in S-MAC with increasing data rate

4.3 Incorporation of Various Protocols inside the XLCA

In order to accommodate each of the cross-layer developments that will be explained in Chapter 5, 6 and 7 there are some requirements inside the XLCA that will be addressed, for each solution, in its correspondent chapter. A summary of these is listed here:

- DirC-MAC (Chapter 5) needs to consider a switched beam antenna at each node, a new directional contention handshaking mechanisms and changes in the initialisation routing packet.
- SSAS (Chapter 6) requires a new initialisation with cluster formations around sinks, the possibility of mounting SBA at the sinks, a hybrid access mechanism (contention and scheduled access), changes in the Adaptive Sleeping and additional adaptive schemes related with the hybrid MAC operated at the sink one-hop cluster.

- Proactive Schemes (Chapter 7) require a mechanism for detection of vulnerable nodes based on radio usage information in addition to the proactive functionality itself.

In addition, for comparison purposes, two MACs, apart from the default C-MAC, have been implemented inside the XLCA framework. There are the TDMA-based LEACH [29] and the polling-based B-MAC [28]. LEACH has its own Routing and MAC layers (it does not require network self-configuration), but keeps the Application and Physical layer of XLCA. On the other hand, B-MAC only changes the control access mechanism inside the Routing-MAC fusion layer and maintains the same initialisation stage and routing that the base solution C-MAC (≡S-MAC) in XLCA.

4.3.1 LEACH

LEACH is a TDMA routing-MAC with a clustering based approach where the network is organised in clusters composed of only the one-hop neighbours around their cluster heads (CH). To reduce the energy overhead caused by frequent clustering formation in LEACH, this process is repeated every 20 frames (frame = packet inter-arrival time). The decision for a node to become a cluster head is based on the number of cluster heads per networks (assumed to be 10% as in [29]) and the number of times that a node has previously been a cluster head; the decision algorithm is proposed in [29]. The routing in LEACH is implicit and thus it does not require the directed diffusion protocol. Nodes inside the cluster send the packets to the CH using TDMA and the CHs forward all the cluster packets to the sink(s) during the forwarding period. If a node does not belong to any cluster it will access the sink directly. To avoid disastrous collision effects during the forwarding period towards sinks, here LEACH is enhanced with a collision-free TDMA access to the sinks.

One disadvantage of LEACH is that it requires CDMA codification among clusters and a high maximum power transmission in order to reach the sink from any network node; this is usually impractical for applications in large networks. In order to reach the sink (centre) from any node location a high power transmission is achieved using a 20dB amplifier (see Tmote mini [103]) raising the CC2420 output power P_r from 0dBm to 20dBm, thus ideally increasing the OD range by 5 times. Some scenarios will require more than one sink to enable full network area coverage.

4.3.2 B-MAC

The operation of channel polling based protocol B-MAC [28] consists in transmitting long preambles before the Data packets; a low power listening (LPL) scheme is assumed where nodes independently wake up to sample the radio channel for activity, turning on the radio when the channel is busy in order to receive a packet. Without sleeping periods, B-MAC provides low latency delivery in event-driven applications; however, its use for periodic traffic applications has lifetime limitations as will be shown in Chapter 6, and specifically in Section 6.3.2. Moreover, the use of long preambles and the existence of the hidden terminal problem cause a high number of collisions in B-MAC.

Because a Polling MAC results very inefficient with the assumption of multi-hop networks and periodic traffic, B-MAC is only compared with SSAS in 6.3.2 with low data rate applications. A four-way handshaking (RCDA) mechanism is used as it offers better performance in B-MAC, avoiding retransmissions due to the high occurrence of preamble collisions. The preambles make the function of the RTS packets. In order to satisfy the data delivery requirement, the B-MAC design parameters have been selected: a preamble length of 2500 bits, a sampling duration of 1ms and a wakeup interval of 10ms (equal to the preamble transmission time, $2500b/250kbps$). An important drawback of the CC2420 radio is that a LPL mode is not supported and it is necessary to turn-on the radio (Rx) to sense the channel [104]. In addition, with a high start-up time (Sleep→Rx) at the CC2420 radio (~4ms, shown in Figure 4.7), the resultant duty-cycle is significantly higher than a 10%, which considerably limits the B-MAC performance. To alleviate the energy consumption in B-MAC, a start-up time of 0.5ms has been assumed in the simulations.

4.3.3 Assumptions in the Evaluation Environment

In the simulations results that will be illustrated and analysed in the next Chapters 5, 6 and 7, unless it is explicitly indicated, the solutions will make use of the functionality and models that have been described throughout 4.1 and the parameters included in Table 4.1.

An important decision in multi-hop networks is the selection of the transceiver output power. In random deployments, decreasing the range will increase the number of hops to the sink, which increases the number of transmissions and contention problems. Simulation results comparing different output powers of the CC2420 showed better consistent performance (throughput and battery usage) with higher power, hence fewer hops to the sink, on average, even though interference problems (collisions) are also increased at higher Tx power because the higher range. An alternative is to use maximum power during the initialisation to set the minimum hop routing trees, but adjust the transmission power in each particular node-to-node link enough to reach the destination, thus reducing power consumption and the signal strength of possible interfering signals. This technique has been broadly suggested to be used in WSNs [69][83]. However, due to the varying channel interference conditions and also the limited output power levels of WSN transceiver (in particular 8 levels for the CC2420) links are more prone to become unreliable if transmission power is reduced; a fact which is general for wireless [84]. Simulations show increasing drop packets, higher delays and worse overall network performance if Tx power is adjusted compared to a solution that uses always maximum Tx power.

In the network topologies that will be evaluated in this thesis, the maximum power state of the CC2420 is assumed for OD transmissions. However solutions using switched beam directional antennas may control the Tx power to adjust the effective gain, thus range, of the radio device.

Having described the based elements of XLCA, the remaining chapters describe the development and optimisations within XLCA of the techniques which provide the targeted adaptability and longevity.

Chapter 5

*Dir*C-MAC: Directional Contention MAC

With the main motivation of improving the base contention solution C-MAC (similar to S-MAC with adaptive sleeping, see 4.1.4), this chapter analyses Directional Contention-based MAC (*Dir*C-MAC) that combines a contention handshaking mechanism with the use of directional switched beam antennas. Co-design techniques are explored in order to profit from the directional capabilities. Heterogeneous sensor nodes, in terms of the kind of antenna mounted, are supported in *Dir*C-MAC with the condition that an omnidirectional antenna mode is required. This solution is included inside of the cross-layer architecture XLCA presented in Chapter 4 and thus entails self-configuration and routing to be achieved with any type of antenna mounted. In essence *Dir*C-MAC reassembles the four-way handshaking C-MAC including power and antenna control to enable directional transmission and reception. The main benefits of using switched beam antennas (SBAs) inside XLCA is first, mitigation of congestion problems (collisions, interferences) due to the limited aperture with directional Tx/Rx and second, a reduction in the number of hops in the routing path trees towards the sinks, as a consequence of a higher directional gain.

Simulation results of *Dir*C-MAC with different handshaking mechanisms and antenna types show important improvements over the omnidirectional base solution C-MAC.

5.1 Congestion Problems and Directional Approach

As previously discussed, adoption of scheduled contention communication schemes can offer attractive features to distributed sensor networks such as energy efficiency, flexibility, scalability and adaptability. However, with a common time frame and space for communications, neighbour nodes need to compete in accessing the radio channel which can produce congestion problems. Several factors such as the number of nodes, the density of nodes, traffic generation rate, duty-cycle, etc will have an impact on the scope of these problems.

In a wide range of WSN converge-casting deployments, the application requirements such as minimum data delivery ratio and maximum delay can be achieved using contention MACs if a correct selection of the frame duration and duty-cycle is made, even if congestion problems are significant. It is possible to reduce congestion by using longer active periods and more relaxing backoff techniques when accessing the channel, however that also implies more energy waste. The backoff design imposes a trade-off between the increase of channel utilisation, with more chances of simultaneous transmissions and the consequent increase in congestion problems. A random backoff mechanism (with variable size shown in Table 4.1) will be assumed in the results described in this thesis.

In any case the limitations of the contention mechanism are prevalent and some changes in the Routing-MAC design such as the adoption of new PHY options are necessary to reduce these problems and to achieve more efficient communications.

5.1.1 Congestion Problems in C-MAC with Omnidirectional Antennas

In order to understand the boundaries of an omnidirectional contention MAC in multi-hop converge-casting applications, the numerical results of this section analyse the main congestion problems of the base communication protocol C-MAC in XLCA. The results represent the average simulation outputs from five different topologies of 100 nodes spread over an area of 500m by 500m and with one sink located in the centre (as shown in Figure 5.1). The duration of the simulations evaluated is 4000s and two types of inter-arrival time applications (20s and 100s) have been assumed. Key parameters such as frame duration and duty-cycle have been selected to achieve at least 90% of data delivery rate at the sink. The main network performance metrics are listed in Table 5.1.

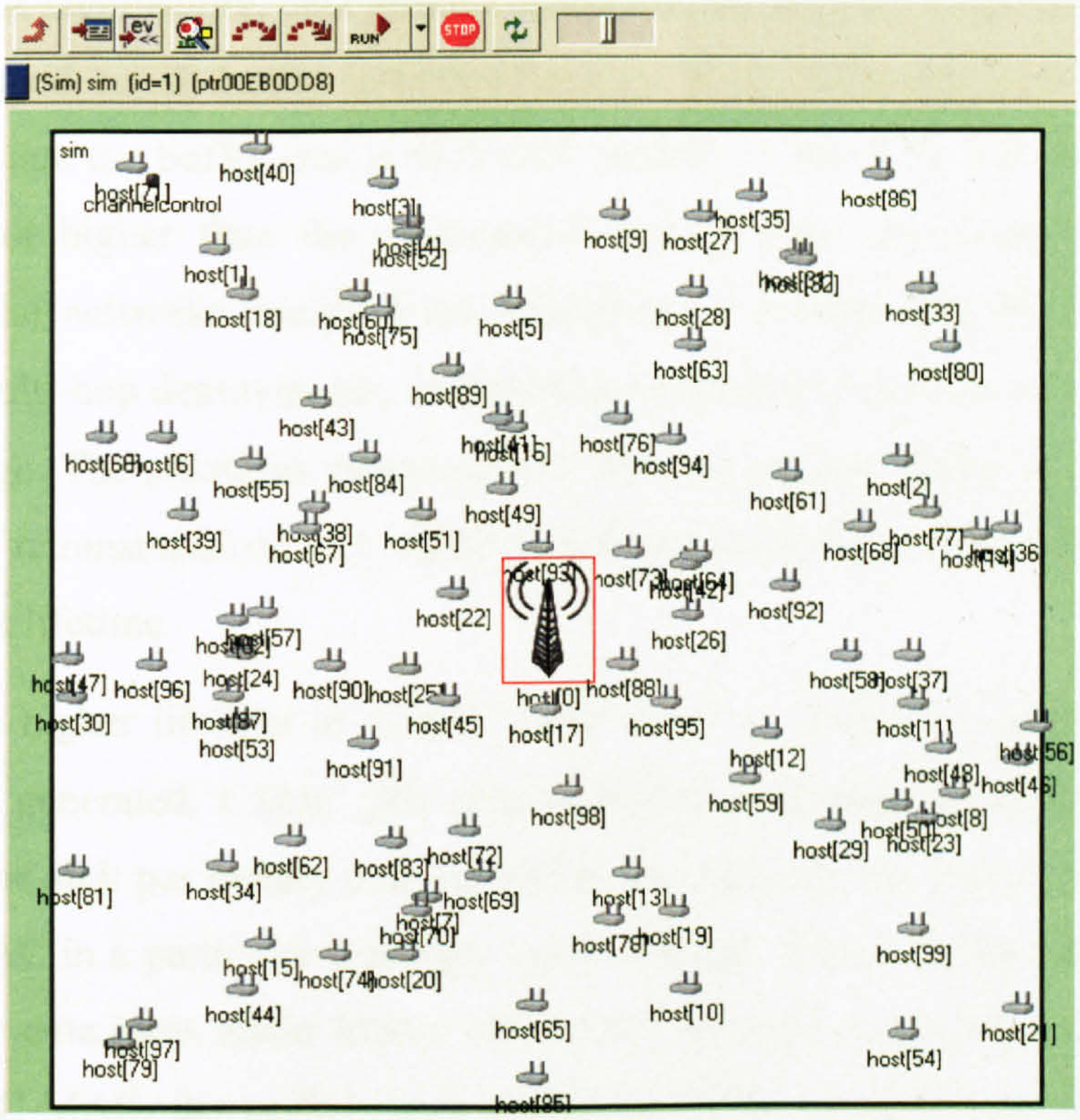


Figure 5.1 – Random network topology with 100 nodes

Table 5.1 - C-MAC: Design Metrics and Overall Network Performance

	Frame Size (seconds)	Duty-Cycle	Lifetime (days)	Efficiency (Pkts/mAs)	Delay (seconds)	ReTxon (%)
CMAC_20s	10.00	6.00	262.13	9.64	14.80	77.63
CMAC_100s	25.00	1.50	1103.32	7.85	50.10	70.03

The lifetime is proportional to the active time required for communications and 4.2 times higher with the lower data rate (1Pkt/100s). A meaningful metric to measure the impact of congestion is data retransmission which represents the most prejudicial collisions; the ones that involve loss of DATA or ACK packets. For both types of application, the percentage of data packets that are retransmitted in the network per data packet that is received in the final destination (sink) is higher than 70 percent. Explicitly each sensing data packet is retransmitted, on average, over 0.7 times along its path to the sink; the assumption being that buffer sizes are adequate for the traffic levels considered.

In the XLCA architecture, data packets remain in the network until maximum user delay is reached or if buffer overflow occurs in a particular node. With the consideration that the buffer size is 4kB (100 packets, Table 4.1) and that the frame duration is not higher than the inter-packet arrival time, the chances of buffer overflow in the networks analysed are negligible. If a high data delivery ratio is required in multi-hop deployments, unavoidable retransmissions can cause excessive energy wastage. The solutions proposed will have as main objective a reduction in the amount of retransmissions of C-MAC in order to raise the network efficiency and hence increase lifetime.

Besides the higher lifetime of *CMAC_100s* shown in Table 5.1, with five times more packets generated, *CMAC_20s* obtains higher efficiency in terms of packets delivered at the sink per battery unit expend in the network. As long as the capacity limit of C-MAC in a particular topology is not reached (state of congestion collapse [106]), higher data rates attain higher efficiency. In order to illustrate the capacity limitation of C-MAC, the performance results in Table 5.2 have considered higher data rates (smaller inter-arrival packet times) in the same five random topologies that have been simulated in the results of Table 5.1. The duty-cycles have been chosen to achieve at least 90% of data delivery ratio at the sink. However with inter-arrival packet time of 5 and 1 second the network reach the maximum capacity of C-MAC and the maximum data delivery achieved is 78% and 37% respectively.

Table 5.2 - Performance with Increasing Data Rate (Congestion Collapse)

Inter-Arrival Pckt (s)	100	40	30	20	10	5	1
Packets per second	0.01	0.025	0.033	0.05	0.10	0.2	1
Duty-Cycle (%)	1.50	3.00	4.00	6.00	12.00	18.00	50.00
Data Delivery Sink (%)	97.73	98.45	98.18	96.94	94.92	78.31	37.42
Efficiency (Pkts/mAs)	7.85	7.93	8.90	9.64	9.27	6.33	5.63

The duty-cycles at these data rates have been adjusted to the congestion collapse point after which higher duty-cycles, thus active times, do not involve increasing data delivery. The efficiency metric in Table 5.2 shows that after the maximum network capacity is reached the efficiency of the network is reduced due to the high level of congestion and associated problems (collisions, retransmission, overhearing).

A better understanding of the network congestion metrics and their impact at different network locations with C-MAC is illustrated in the Figure 5.2, Figure 5.3 and Figure 5.4. The graphs show the average value per node of the five topologies where nodes are classified by the distance in hops from the sink. For example, in Figure 5.2(a), each one-hop node in *CMAC_20s* will experience on average 4357 collisions during the 400 frames (4000s) in which every node has generated 200 packets.

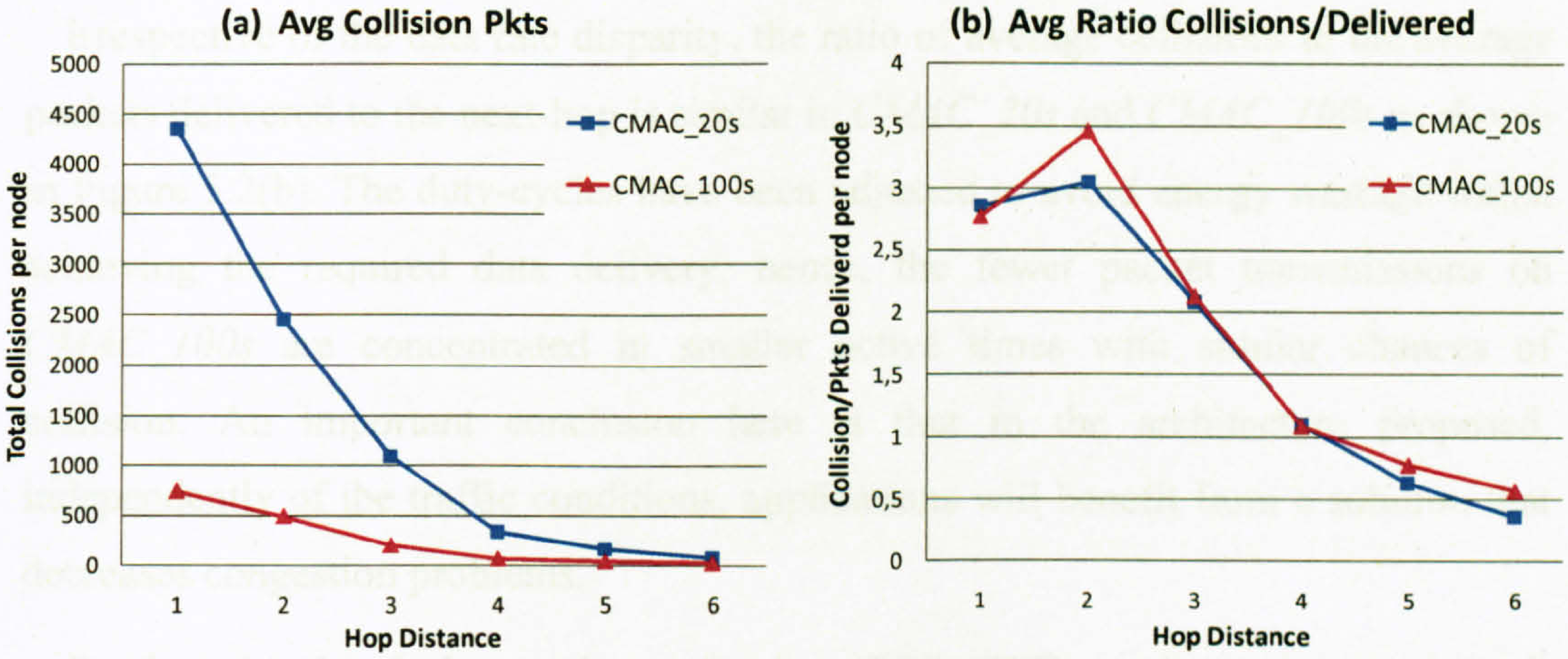


Figure 5.2 - Collisions per hop in C-MAC

With the escalating traffic, the number of collisions is notably increased at nodes with fewer hops from the sink due to the expected funnelling effect. In proportion to the packets transmitted, fewer collisions occur in *CMAC_100s*. The majority of these collisions are helped by the hidden terminal and idle listening problems among the contending nodes. Frequently collisions are caused by RTS and CTS packet transmissions from hidden terminals that collide in receiver nodes located between them. When a RTS or CTS collision happens in the intended receiver, the handshaking process is interrupted and nodes need to backoff again, wasting more time and decreasing the network efficiency.

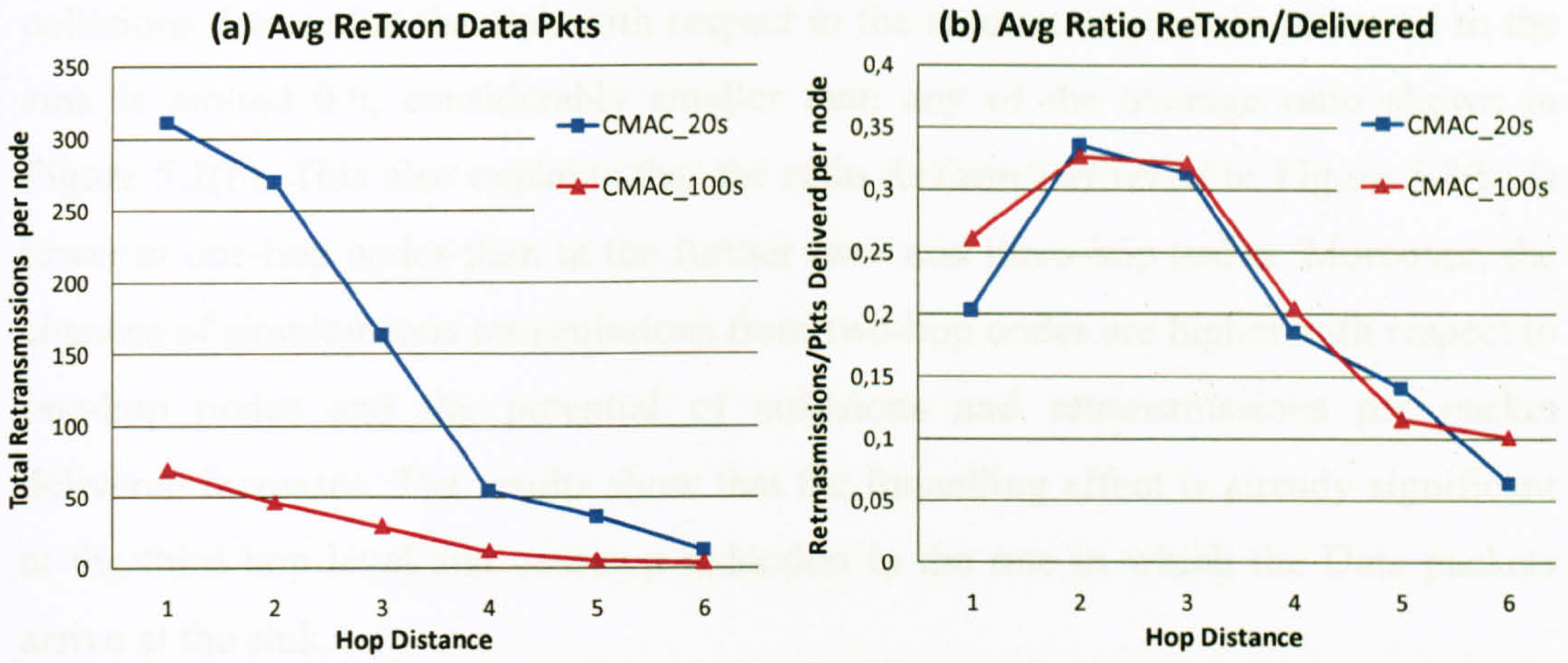


Figure 5.3 - Retransmissions per hop in C-MAC

Irrespective of the data rate disparity, the ratio of average collisions to the average packets delivered to the next-hop is similar in *CMAC_20s* and *CMAC_100s* as shown in Figure 5.2(b). The duty-cycles have been adjusted to avoid energy wastage whilst achieving the required data delivery; hence, the fewer packet transmissions on *CMAC_100s* are concentrated in smaller active times with similar chances of collision. An important conclusion here is that in the architecture proposed, independently of the traffic conditions, applications will benefit from a solution that decreases congestion problems.

On the other hand, due to the contention (RTS, CTS) mechanism, only a small percentage of these collisions involve DATA or ACK collisions and thus require retransmission. The average number of retransmissions per node at the different hops is represented in Figure 5.3(a), and Figure 5.3(b) shows the fraction of these to the average packets delivered. The Data packets generated further from the sink have accumulatively more chances to be retransmitted. Although the queue management of C-MAC selects the oldest packets to be transmitted first (if the maximum delay is not exceed), peripheral network packets are prone to experience higher delays and higher probability of loss. As with collisions, retransmission problems are related to traffic intensity (i.e. packets forwarded/active time used).

However, in practice, the sink CTS packets are not received in every one-hop node because these may be in an *Idle* state (scheduling a NAV) or, alternatively, when collisions in the CTS reception occur (hidden terminal). Nevertheless, the ratio of collisions detected at the sink with respect to the amount of packets delivered to the sink is around 0.6, considerably smaller than any of the average ratio shown in Figure 5.2(b). This also explains that the ratio *ReTxon/Delivered* in Figure 5.3(b) is lower at one-hop nodes than in the further two- and three-hop nodes. Moreover, the chances of simultaneous transmissions from two-hop nodes are higher with respect to one-hop nodes and the potential of collisions and retransmissions per packet delivered increases. The results show that the funnelling effect is already significant at the third hop level and causes a reduction in the rate in which the Data packets arrive at the sink.

An additional congestion problem is the overhearing of Data and ACK packets, represented in Figure 5.4(a). The contention mechanism is designed to avoid overhearing, and therefore energy wastage, deferring contending nodes with the NAV scheduling technique after a RTS or CTS is received. However, because collisions and unawareness of ongoing transmissions, during such NAV scheduling, the amount of overhearing packets at one-hop nodes is even higher than the average number of packets forwarded to the sink. Yet, simulation results have proved that the significant reduction of energy consumption associated with the scheduling of NAVs (*Idle* state) prevails over the problems derived from the increase of unawareness.

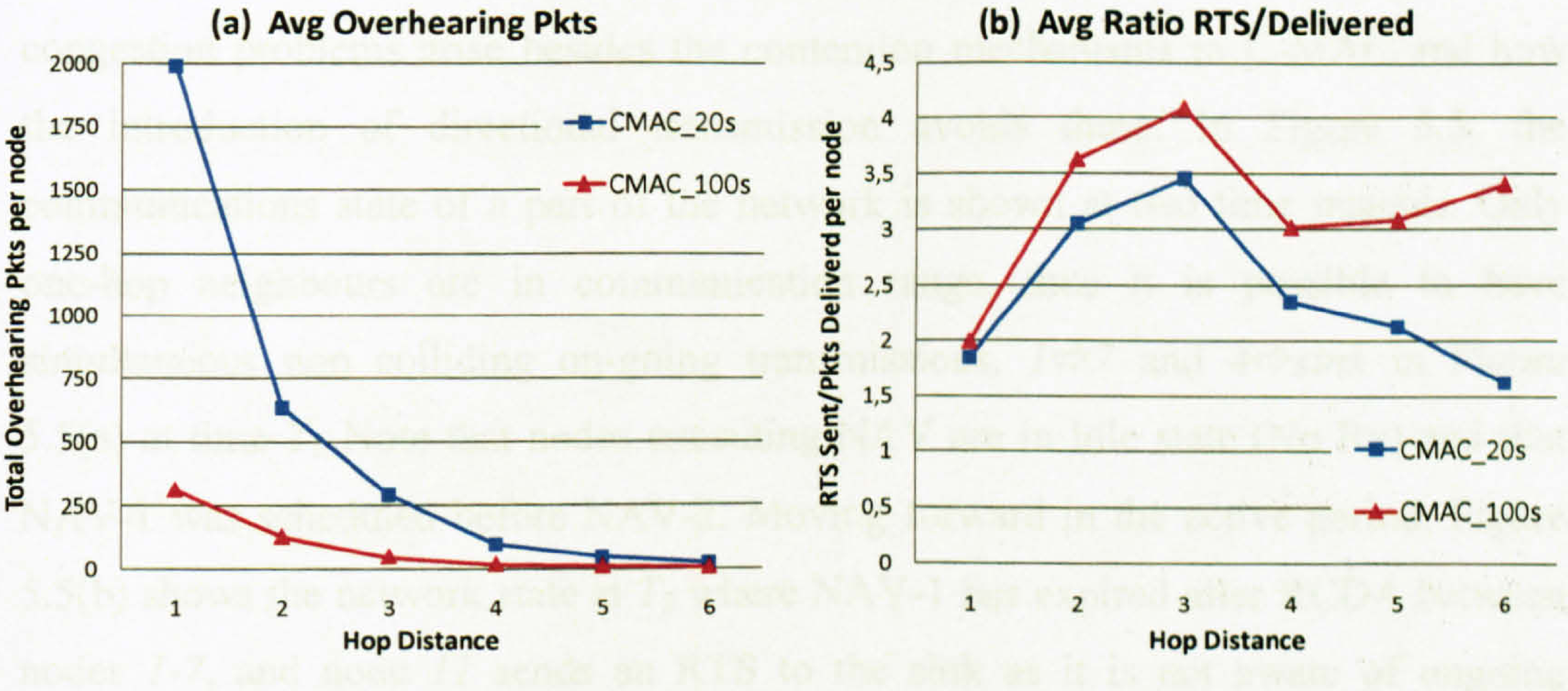


Figure 5.4 - Overhearing and RTS efficiency per hop in C-MAC

The RTS re-transmissions are cause and effect of the cited collisions and Data retransmissions problems. It is difficult to circumvent this problem in the type of applications being considered here (multi-hop network with 100 nodes in Figure 5.1), and time-sharing access where all nodes generate packets); relaxation of backoff access techniques increases RTS success but it also incurs lower efficiency. A more feasible solution can attempt to reduce the negative impact (collisions) from the persisting RTS transmissions.

The co-design techniques proposed in this and following *chapters* exhibit the effectiveness of reducing the quantity or impact of the exposed congestion problems.

5.1.2 Introducing Directional Antennas in a Contention Based MAC

*Dir*C-MAC proposes the integration of directional transmissions inside C-MAC with the inclusion of directional antennas within XLCA, in particular using switched beam antennas. The hypothesis being that if DATA and ACK packets are transmitted and received directionally, congestion problems such as retransmission, collisions and overhearing can be considerably decreased. This straightforward variation over C-MAC does not require complicated directional MAC designs and aligns with the practicalities of having limited pointing capability using SBAs; also satisfy the XLCA requirement of self-configuration and routing.

The next Figure 5.5 and Figure 5.6 exemplify the manner in which some congestion problems arise besides the contention mechanisms in C-MAC and how the introduction of directional transmission avoids these. In Figure 5.5, the communications state of a part of the network is shown at two time instants. Only one-hop neighbours are in communication range, thus it is possible to have simultaneous non colliding on-going transmissions, *1*⇨*7* and *4*⇨*sink* in Figure 5.5(a) at time T_1. Note that nodes executing NAV are in Idle state (No Rx) and that NAV-1 was scheduled before NAV-2. Moving forward in the active period, Figure 5.5(b) shows the network state at T_2 where NAV-1 has expired after RCDA between nodes *1*-*7*, and node *11* sends an RTS to the sink as it is not aware of ongoing previously started communications of node *4* to the sink (the hidden terminal problem). The collision (✗ in Figure 5.5(b)) of this RTS packet will cause data loss at the sink and consequently for onward retransmission, but also its overhearing will cause unnecessary NAV at nodes *3* and *7*.

Using directional transmissions can reduce the mentioned OD problems, avoiding failure of ongoing transmissions and enabling started ones to continue. Keeping the four-way handshaking, one possible directional MAC solution is to send RTS and CTS in an omnidirectional mode whilst the DATA and ACK packets are transmitted and received using the directional beams. In the previous example of Figure 5.5, considering node 4 and the sink Tx-Rx beams pointing to each other during Data transmission will avoid the collision with *11*'s RTS as shown in Figure 5.6(a). In this way spatial reuse can be increased without retransmission consequences; e.g. in Figure 5.6(b) the handshaking *3*⇨*11* is applicable.

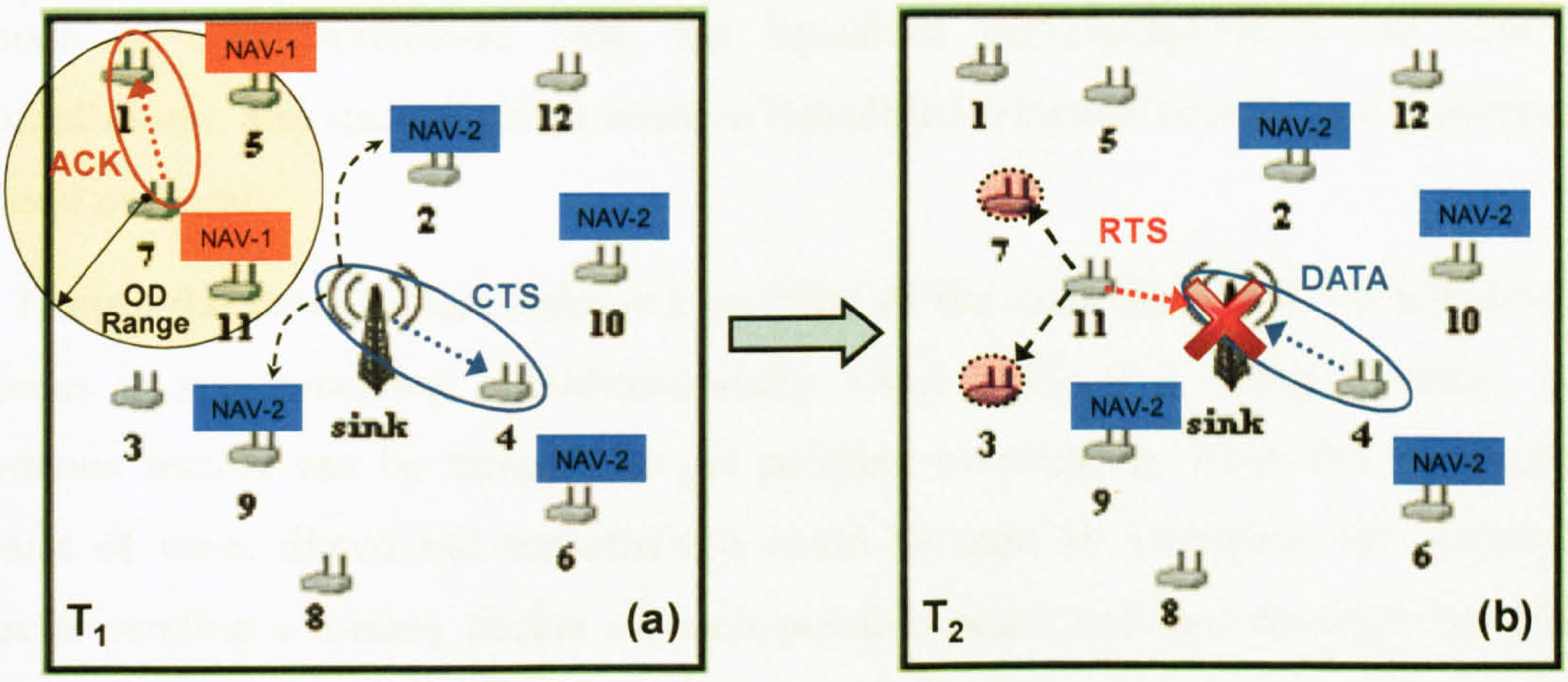


Figure 5.5 – CMAC congestion problems. Network states at T_1 (a) and T_2 (b)

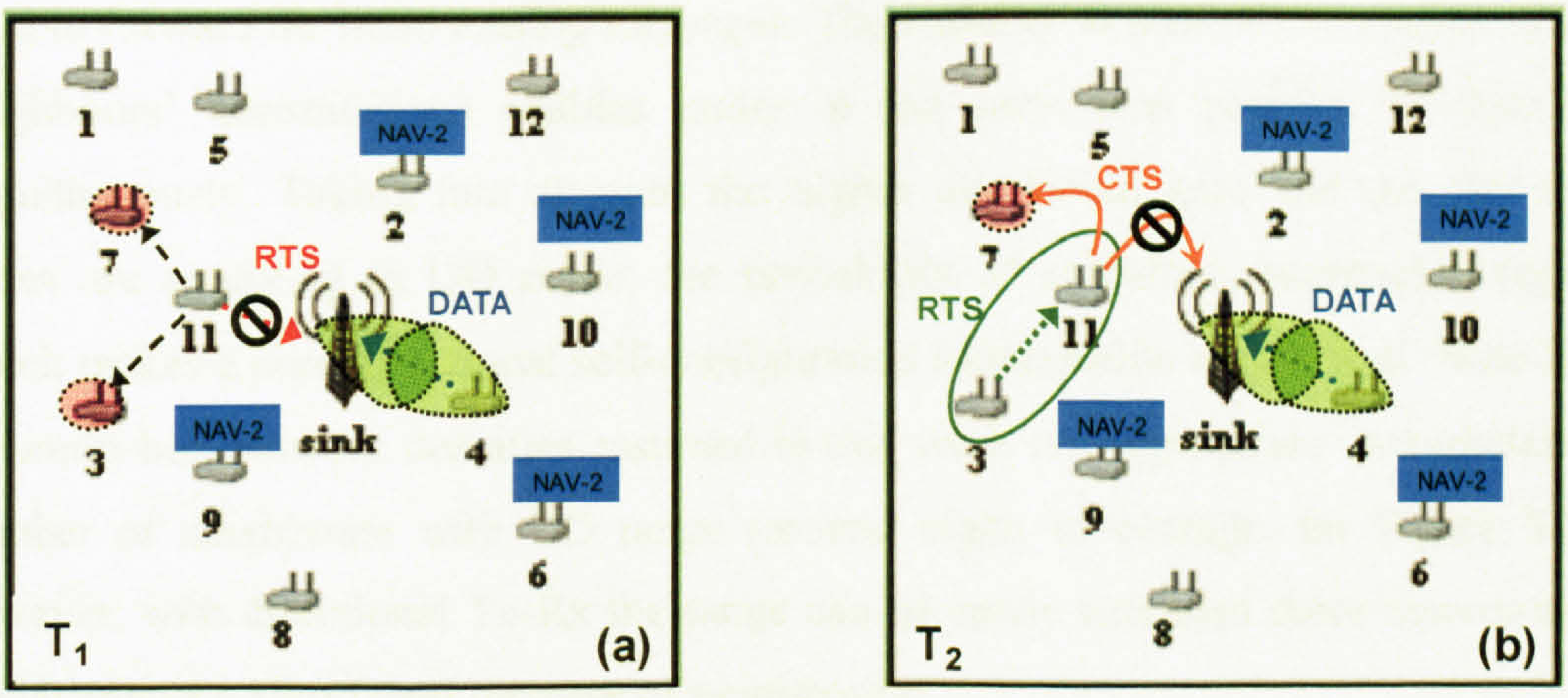


Figure 5.6 – Collision avoidance (a) and spatial reuse (b) with directional SBA

5.2 Directional Co-Design Considerations

With reference to Figure 5.6 it is envisioned that the introduction of directional antennas can reduce retransmission and overhearing problems and also increase the spatial reuse, all translating into higher network efficiency. However a well designed MAC needs to consider several implications of having directional communications. This section covers the principal issues that arise when switched beam directional antennas are introduced into the design of contention-based MACs and particularly within the XLCA architecture in Chapter 4 .

5.2.1 The Need for Omnidirectional Communications

There are two main reasons in XLCA that require the use of an omnidirectional mode of communications: first, the broadcast self-configuration and routing initialisation, and second, the absence of scheduled communications in a contention based protocol.

During the initialisation, unknown position of the node itself and its neighbours forces to stay receiving omnidirectionally. Once a signal is being received, the antenna sectors can be sampled to get pointing information. From the transmitter point of view, directional transmission could be used by switching the antenna's sector sending a routing packet on each possible beam and thus covering the 360° coverage. This can be done without difficulty at the sink as it is the beginning of the broadcasting process. However the problems arise when the following hops' nodes need to forward the hello routing messages. The inability to hear (CSMA) directional neighbours' transmissions enables nodes at the same hop position to transmit simultaneously. Taking into account the higher directional gain and the fact that nodes are receiving in OD mode, the probability of collisions increases abruptly which makes a pure directional self-configuration initialisation unpractical. Note that the multi-hop network densities assumed in this work are appropriate to a moderate number of neighbours with OD range (around eight, in average, for Figure 5.1); however, with directional Tx-Rx the range can be easily extended more than double which entails a significant increase of neighbours.

Regarding the second reason, during the nodes-to-sink forwarding process, uncertainty in packet arrival direction from the possible senders, which is characteristic of contention-based MACs, may require the existence of an omnidirectional antenna mode in Rx. In some cases, depending on the antenna beam width and location of senders, a node can receive adequately from all its child-nodes using just one of the available sectors. However, the limited coverage may impede this node from detecting an ongoing transmission from its next-hop in the routing tree. There is a trade-off between the increase of spatial reuse and the increase probability of future collisions.

On the other hand, transmitting nodes which already know the direction of their next-hop neighbours are able to send the data packets directionally which, for instance, benefits the network spatial reuse. Nevertheless, if nodes do not make use of an OD (RTS/CTS) contention mechanism the chances of collision will increase.

Irrespective of the handshaking mechanism the need of an omnidirectinal mode is assumed during the initialisation period. Hence the use of switched beam antennas is justified as it is also possible to form an omnidirectional radiation pattern by combining the multiple beams. The potential gain will be reduced in Tx as the output power is split between the different antenna elements (sectors), however OD Rx with directional elements achieves higher gain with respect to the isotropic antennas.

5.2.2 Power Control and Pointing abilities

Capacity to control the transmission power in WSN transceivers allows adjustment of the range and therefore the number of neighbours that can be reached. In Figure 5.7(a), node A can communicate with node C using low power without affect an ongoing communication in node D. Incorporating directional antennas adds another dimension as nodes are able to point and adjust power to increase spatial reuse and reduce potential interference. However exploiting these capabilities requires reconsideration of contention-based MAC functions like carrier sensing, backoffs or contention mechanisms (RTS, CTS) as neighbours no longer share a common and unique medium channel. In Figure 5.7(b) the inability to transmit data from node A to D does not imply that a packet cannot be transmitted or received to/from another neighbour. Rather than retry transmitting to the same destination, MAC schemes can take into account the spatial reuse capability provided by directional antennas.

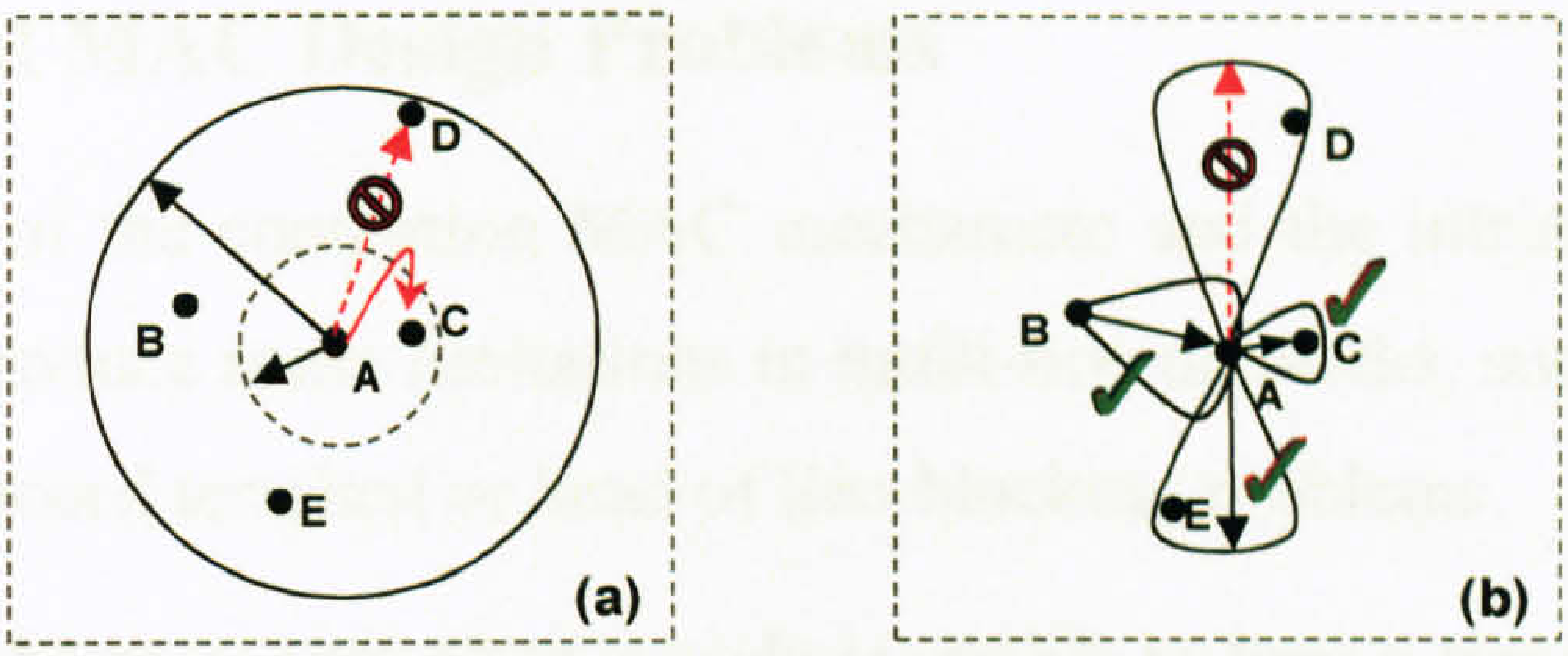


Figure 5.7 – Power control (a) and pointing ability (b)

In *Dir*C-MAC, MAC co-design with directional antennas requires both, power and pointing control, in order to profit the directional capabilities. With the aim of selecting the best antenna sector and the necessary output power to reach a specific neighbour, radio link measurements such as signal strength (RSSI) and direction of arrival (DoA) are essential. It is assumed that the pointing information at the Tx and Rx is extracted from the initialisation period during neighbour discovery where the opportunity to select the best beam is possible if a training sequence is added to the hello messages. Alternatively, the RTS/CTS handshaking process could be used although the extra transmission required will increase the control data packet overhead. Nevertheless assuming that nodes are static, the initial pointing information remains valid for the entire network life.

It is important to bear in mind that the initialisation process, although using OD Tx and Rx, assumes the characteristic radiation pattern of the different switched beam antennas, which has been shown in the antenna modelling Section 4.1.8. Consequently the routing scheme (next-hop selection) is influenced by the higher gain in omnidirectional Rx mode of the switched beam antennas. For instance, the increasing gain enables the reduction of the average number of hops towards the sink compared with a solution that uses pure OD antennas. The performance evaluation in section 5.4 demonstrates the advantage of reducing the number of hops, hence the amount of inter-nodes packet transmissions. Nevertheless, the increase in congestion avoidance, associated with the use of directional transmissions, is the main advantage when compared to OD systems. Indeed, *Dir*C-MAC solutions, that reduce the output Tx power during the initialisation in order to get similar range to the OD C-MAC alternative, also achieve significant improvements.

5.2.3 Directional MAC Design Problems

The combination of the contention MAC mechanism and the intrinsic directional radiation pattern introduce some limitations in multi-hop networks, such as deafness, hidden terminal, exposed terminal or head of line blocking problems.

The **deafness problem** occurs when a node is unable to hear a transmission as its antenna is pointing in other direction. In Figure 5.8(a) node E fails to communicate with C because C's antenna is beamformed towards A. With the assumption that the directional mode is used for Data/ACK Tx and Rx, deafness will always be advantageous providing that nodes return to an OD reception state after an ongoing handshaking sequence ends. In the previous example of Figure 5.6(a) a collision is prevented during the reception of the Data packet at the sink due to the deafness issue.

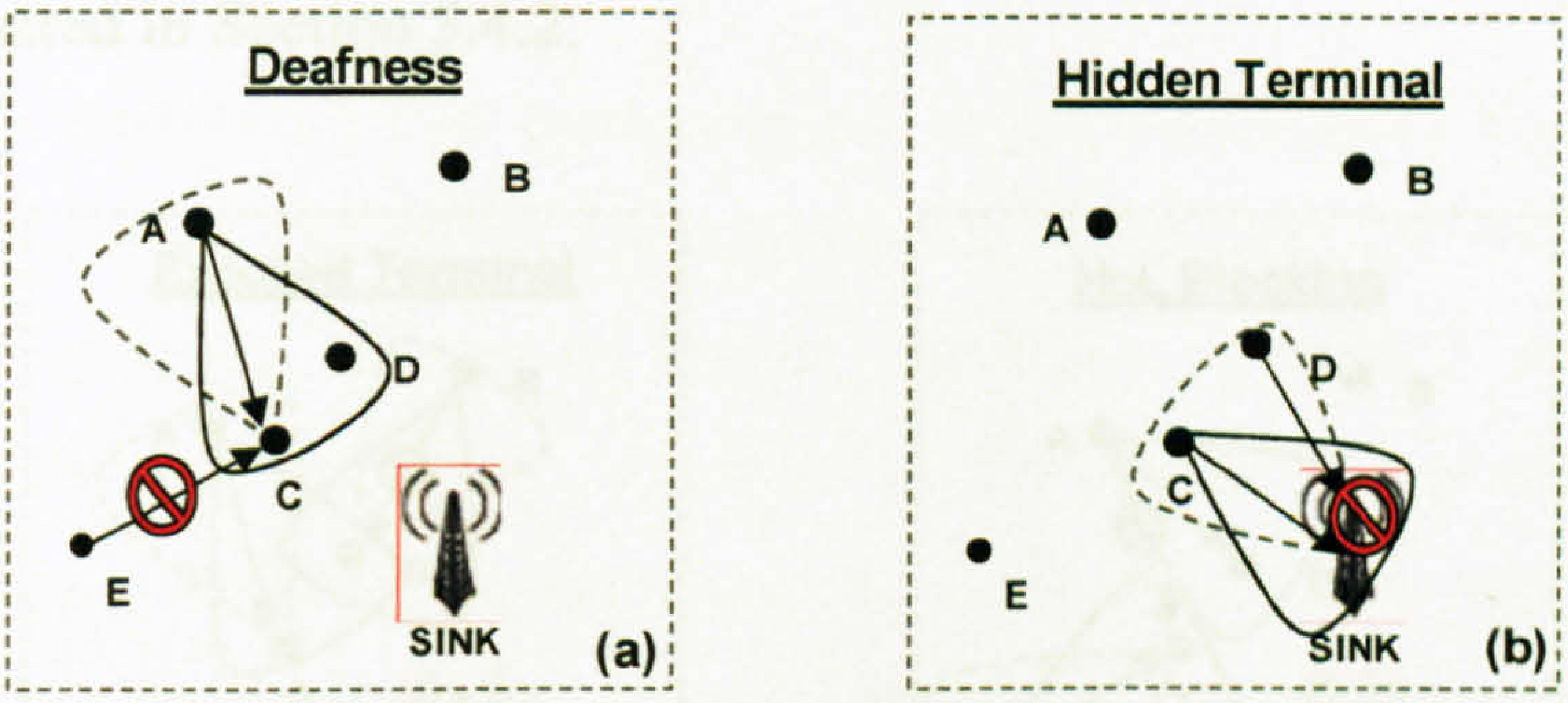


Figure 5.8 – Deafness (a) and hidden terminal (b) with directional antennas

The **hidden terminal** problem occurs when a node is not aware of an ongoing communication between a pair of nodes when its intended transmission (control, data packet) can make the ongoing one unsuccessful. In Figure 5.7(b), node D (earlier communicating with B) is not aware of the communication C⇨SINK and a collision can occur if D decides to forward a packet to the sink. As stated earlier, the scope of this problem is dependent on the MAC operation; usually the hidden terminal is caused by unheard RTS/CTS and promoted by the NAV scheme adopted in C-MAC.

However the negative impact is reduced using directional transmissions as the collision probability decreases.

The **exposed terminal** is a characteristic problem of CSMA scheme helped by RTS/CTS exchange; two node-pairs are forbidden to transmit simultaneously even though these simultaneous transmissions will not collide. It can also happen if directional handshaking is used. For instance, in Figure 5.9(a), node A starts a transmission towards C and D becomes CSMA blocked, thus interrupting the BD link. The proposed SYN-DMAC [105] address this problem in ad-hoc networks, however the solution proposed requires a strict synchronisation scheme along the whole network.

The impact of the hidden and exposed terminal, can be limited if the contention mechanism avoids OD transmissions, for example by sending data packets directionally to the destination. However issues such as the realistic beam width limitation of SBAs and the need of OD reception, in the absence of scheduled packet exchange, make a two way handshaking mechanism more predisposed to congestion problems. This and other handshaking techniques have been included in *Dir*C-MAC and are compared in Section 5.4.2.

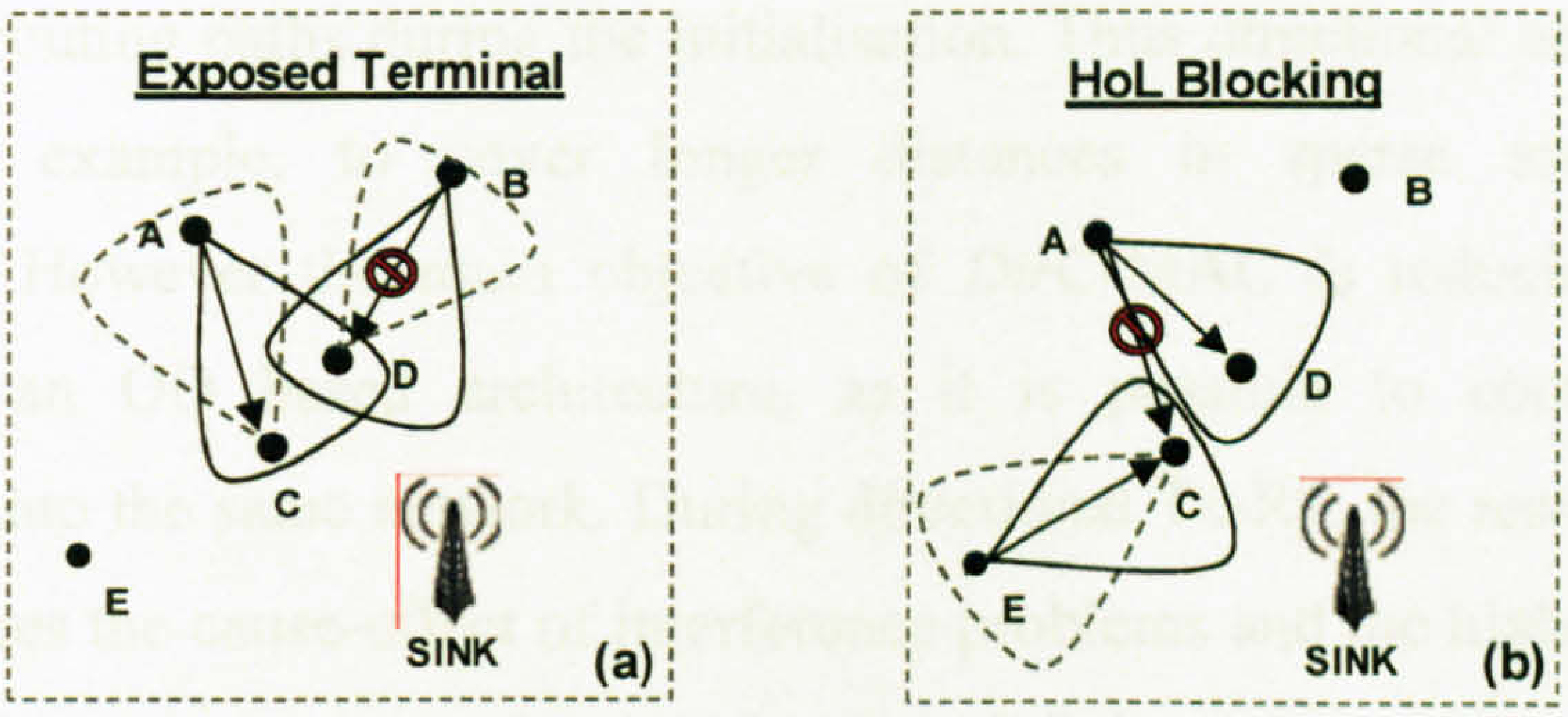


Figure 5.9 - Exposed Terminal (a) and HoL Blocking (b)

Finally, the **Head of Line (HoL) blocking** occurs when the destination of next packet in the queue (head) is unavailable and consequently the transmitter needs to backoff and retry later. Meanwhile there can be other packets for other available next-hop destinations waiting unnecessarily. This is a traditional problem in contention-based MACs that try to completely send a packet before trying another, although these other packets can be transmitted without causing interference. The introduction of directional transmissions permits to cancel the HoL blocking with non-colliding simultaneous communications. In nodes-to-sink applications addressing the HoL blocking problem is only possible by changing to the next-hop neighbour available, therefore altering the route towards the sink. Adding routing strategies to the use of directional antennas can further benefit the network performance. However, this is outside the scope of the current study that concentrates in the MAC co-design with switched beam antennas.

5.3 *Dir*C-MAC Co-Design

Motivated by the analysis of congestion problems with scheduling contention MAC (Section 5.1), *Dir*C-MAC is proposed to adapt the base OD C-MAC protocol to profit from the use of directional transmissions with switched beam antennas. The implementation of *Dir*C-MAC is included inside the XLCA platform and replaces the base MAC (C-MAC). The *Dir*C-MAC solution makes use of the directional antenna model presented in Section 4.1.8 and requires modifications in the initialisation stage that are described in the next Section 5.3.1.

The use of omnidirectional transmissions is not an obligatory requirement to establish the routing paths during the initialisation. Thus directional antennas can be adopted, for example, to cover longer distances in sparse sensor network deployments. However the main objective of *Dir*C-MAC is reducing congestion problems in an OD based architecture, as it is possible to combine antenna technologies into the same network. During directional Tx-Rx, the restricted antenna aperture reduces the cause-effect of interference problems and the higher gain allows lower transmitter power. Nonetheless, directional links using maximum Tx power can be used to interconnect distant gateways which belong to different sensor clusters, for example.

5.3.1 Configuration and Routing

The initialisation phase of XLCA is reproduced in *Dir*C-MAC. The sequential process in which neighbour discovery and broadcast of application/routing parameters occur is shown in Figure 5.10(a) for OD antennas. The numbers indicate the progression of the transmissions initiated at the sink. Node C stays listening for a fixed period once a first routing packet is received (i.e. from D) so that other possible one-hop neighbours can be recorded; after a next-hop decision is made, C continues the forwarding process informing further hops of its best routing alternative (hops and estimated distance to the sink). B and D also remain receiving for a bit longer with the intention of completing the neighbour table and to check which of them are potential senders. Early routing decisions establish the routing trees shown in Figure 5.10(b) after the initialisation ends.

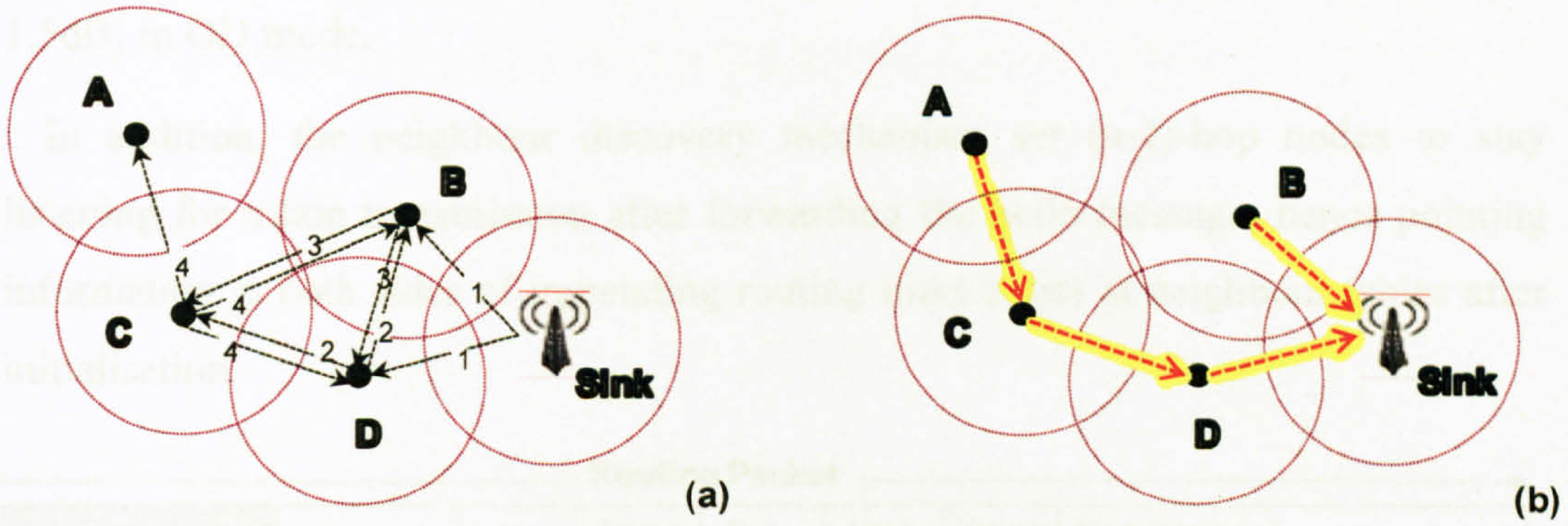
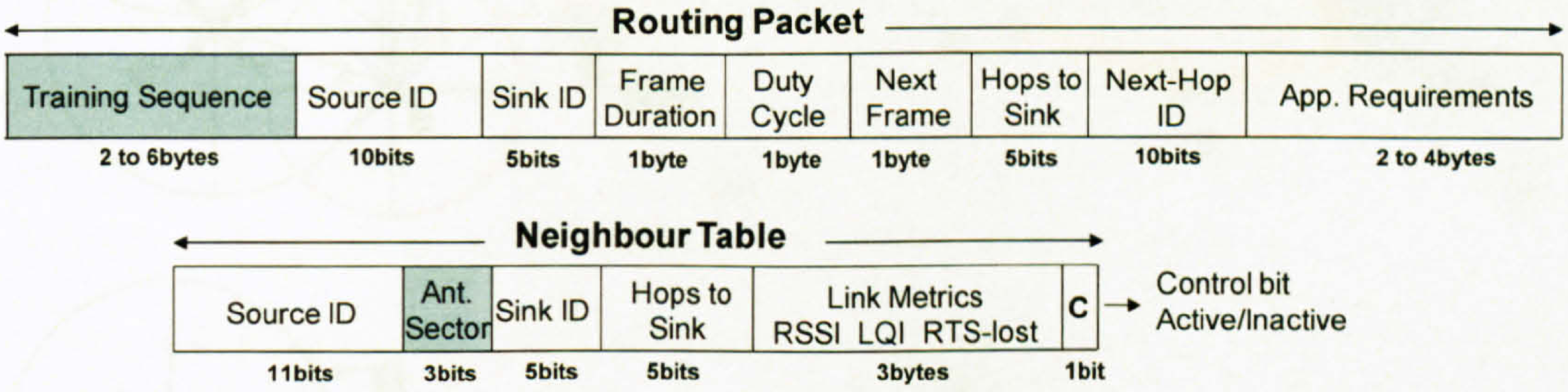


Figure 5.10 – Initialisation: Neighbour discovery and routing with OD antennas

The radiation particularities of the switched beam antenna model may cause the routing trees to differ with respect to the ones obtained with an OD antenna based system. Overlapping of the radiation patterns for individual sectors can shape a fairly accurate OD radiation equivalent as explained in Section 4.1.8. Moreover the number of directional elements (sectors), the antenna orientation with respect to neighbours and the output power used during initialisation determines the next-hop routing selection. Independently of the number of sectors, it is assumed that every node has one sector pointing to the North direction (homogeneous modelling approach); if a Grid topology is not considered, the ability to point a neighbour at the peak beam gain is arbitrarily decided by the random nodes positions. For example, a node with a four sectors antenna can direct the beam in four fixed directions, only neighbours in the North-South or East-West axes of the transmitter node observe the beam maximum gain.

During the broadcast interchanging of *hello* messages, a training sequence is added at the beginning of each packet (Figure 5.11). Any node that detects a transmission samples each of the available antenna inputs (sectors) to determine the best sector selection towards the new discovered neighbour; after, it then reverts to the OD mode. Before *n*-hop nodes continue the sequential forwarding process, a routing decision is made with the selection of the best (*n*-1)-hop neighbour. The selection is made among the RSSI measurements on the training sequence of each (*n*-1)-hop neighbour. Therefore next-hop choice depends on the intrinsic gain of the antenna elements in reception and the sectors' orientation to the possible routing alternatives. The modelling assumption sets the intrinsic antenna gain to be reduced by 30% (-1.5dB) in OD mode.

In addition, the neighbour discovery mechanism set (*n*-1)-hop nodes to stay listening for *n*-hop transmission after forwarding the hello message; hence pointing information at both sides of impending routing links exists at neighbour tables after initialisation.



Training Sequence	Source ID	Sink ID	Frame Duration	Duty Cycle	Next Frame	Hops to Sink	Next-Hop ID	App. Requirements
2 to 6bytes	10bits	5bits	1byte	1byte	1byte	5bits	10bits	2 to 4bytes

Source ID	Ant. Sector	Sink ID	Hops to Sink	Link Metrics RSSI LQI RTS-lost	C
11bits	3bits	5bits	5bits	3bytes	1bit

Figure 5.11 – Routing packet and Neighbour table mapping

If Tx power is not reduced during the configuration period, the higher SBAs Rx gain in OD mode increases the range of the links and thus communications with fewer hops than OD C-MAC are possible. An example of how neighbour discovery takes place in *Dir*C-MAC, with two different output powers, is illustrated in Figure 5.12 for the same scenario as in Figure 5.10. The examples focus on the routing alternatives of node A. In Figure 5.12(a) the maximum CC2420 output power is used in Tx (0dBm), thus the effective gain ($P_t \cdot G_t$) is 1 if the total power is split to the four directional antenna elements. Accounting for the beam overlapping, nodes B and D accomplish a similar Tx range with respect to Figure 5.10. However the higher Rx gain ($0.7 \cdot G_t$) of node A provided by the *East* directional SBA element enables listening the B *hello* packet. Consequently node A is in this scenario two hops from sink and its routing tree towards the sink in Figure 5.12 (b) diverges with respect to the one in Figure 5.10(b). On the other hand, similar links range (Tx-Rx) to the OD antenna case is possible if the Tx power is decreased during the initialisation period, as shown in Figure 5.12(c). In this manner the routing trees in Figure 5.12(d) coincide again with Figure 5.10(b).

Once the routing is done, a design decision arises in *Dir*C-MAC on which output power should be used if nodes start a directional transmission. For example, the Tx power used by node A to reach node C in Figure 5.12(d) is not sufficient to contact node B when this routing alternative is available in Figure 5.12(b).

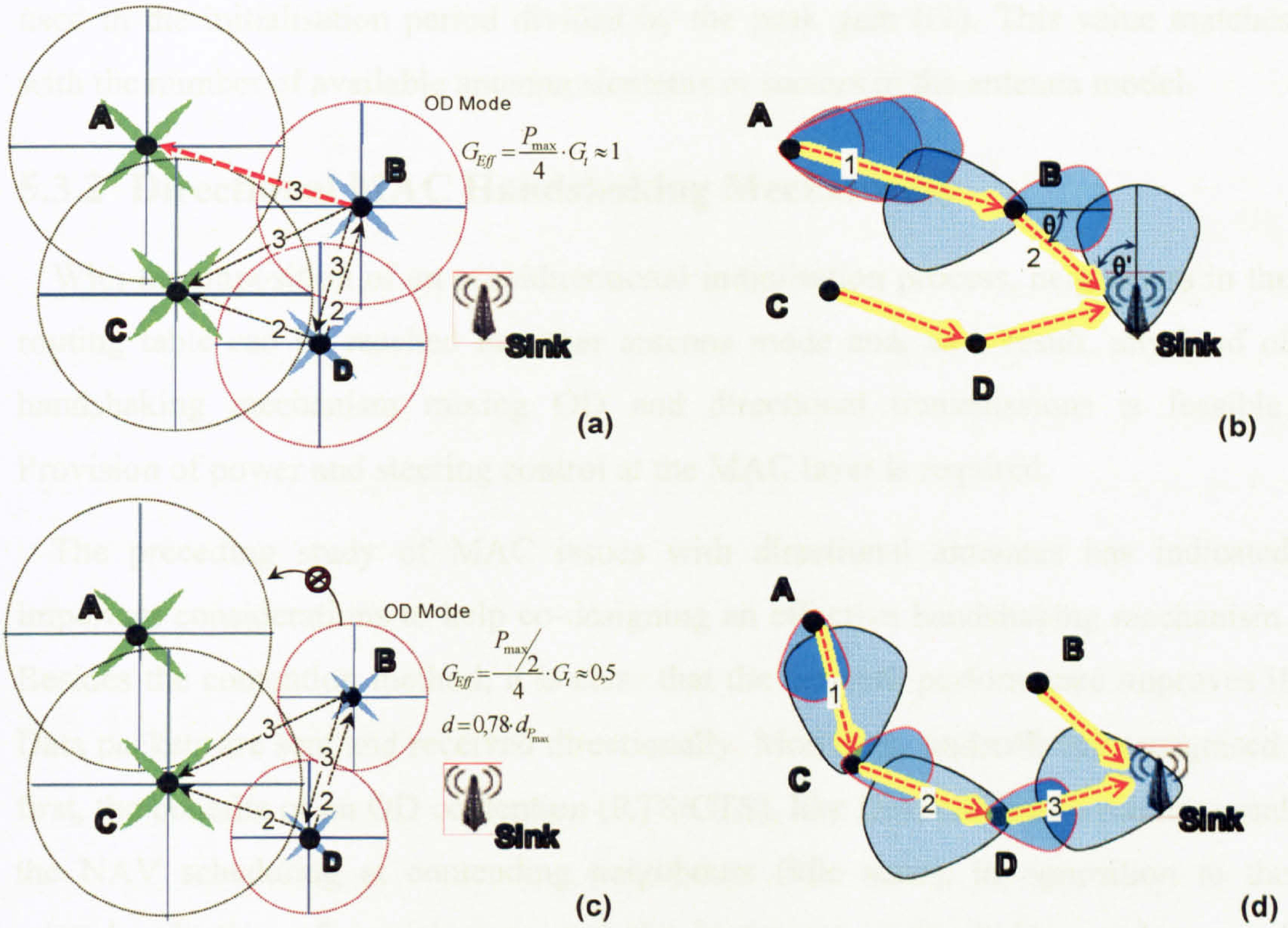


Figure 5.12 – Initialisation: Neighbour discovery and routing with SBA antennas

In a random topology, contrary to a grid topology for example, a node cannot discern the ability of its neighbours to steer the antennas towards it, although the best receiving sector towards a specific neighbour node identified during the neighbour discovery process should correspond with the best choice in transmission. Ideally sector beams of a pair of nodes can point to each other at the peak gain direction. In this situation output power could be divided by $(G_t \cdot G_r)$ obtaining similar range to a OD solution; i.e. same numerator $(P_t \cdot G_t \cdot G_r)$ in (3). In the worst case scenario, a mismatch up to half of the beamwidth at each link side (as shown in Figure 5.12(b) on the B-Sink link) allows a reduction in power of no more than $(\frac{G_t}{2} \cdot \frac{G_r}{2})$.

In addition nodes in the Rx state may be waiting in the OD mode or even be restricted in pointing capability when traditional OD antennas are mounted. With the intention of guaranteeing reception and a good SNIR level, a general assumption in *Dir*C-MAC imposes that directional transmission power should be equal to the one used in the initialisation period divided by the peak gain (G_t). This value matches with the number of available antenna elements or sectors in the antenna model.

5.3.2 Directional MAC Handshaking Mechanisms

With the imposition of an omnidirectional initialisation process, neighbours in the routing table can be reached in either antenna mode and, as a result, any kind of handshaking mechanism mixing OD and directional transmissions is feasible. Provision of power and steering control at the MAC layer is required.

The preceding study of MAC issues with directional antennas has indicated important considerations to help co-designing an effective handshaking mechanism. Besides the contention method, it is clear that the network performance improves if Data packets are sent and received directionally. Moreover, tradeoffs are recognised: first, the benefits of an OD contention (RTS/CTS), like Data collision avoidance and the NAV scheduling at contending neighbours (idle state), in opposition to the related reduction of spatial reuse and the increment of the hidden and exposed terminal problems; second, the benefits of a two-way (Data-ACK) directional handshaking exchange with higher spatial reuse and prevention of overhearing and hidden/exposed terminal problems, opposed to the increasing vulnerability to Data collisions at the uninformed receivers in OD state, and also to the high increase of idle listening lacking of a NAV scheduling mechanism.

In order to evaluate these tradeoffs three different handshaking mechanisms have been proposed. These three mechanisms are compared in section 5.4.2.

Four-way handshaking (RCDA): it is the default contention mechanism in DirC-MAC which is compliant with that proposed in C-MAC. The distinctive variation is that the Data and ACK packets are sent and received directionally. The RTS informs receivers of the starting of handshaking, and thus these can steer the antenna after sending the CTS. As is the case with C-MAC, control packets enable the scheduling of NAVs.

Two-way handshaking (DA): in order to avoid control packet overheads this mechanism disregards the use of RTS/CTS and a two-way handshaking method sends the data directionally to the destination, assuming a CSMA access method. With the absence of an advertising mechanism receiver nodes remain in the OD mode and are more susceptible to collisions. In addition the NAV scheduling is disabled without RTS/CTS.

Inform Beacon (BDA): in this solution, prior to sending the Data packet, an OD inform beacon packet allows first, the intended receiver to be informed and point the antenna, and second, the adjacent neighbours to know about the subsequent data transmission. The beacon acts as a RTS and permits the scheduling of NAV on possible competing neighbours. In this way collisions can be notably reduced at the same time that the control packet overhead is relaxed and spatial reuse is increased with the absence of CTS packets.

5.4 Performance Evaluation

A comprehensive analysis of the impact of the use of directional antennas in *DirC*-MAC has been conducted by extensive simulations of the platform XLCA in various scenarios and different application requirements. Representative results have been considered to show the benefits of *Dir*C-MAC with respect to C-MAC (Section 5.4.1), assess the different directional handshaking mechanisms (Section 5.4.2) and compare *Dir*C-MAC with the TDMA-based approach LEACH (Section 5.4.3). Comparisons with the channel polling protocol B-MAC are shown in Chapter 6.

5.4.1 Impact of Directional Antennas

In this section the impact of introducing directional antennas in C-MAC is analysed. The default *Dir*C-MAC with four-way handshaking (RCDA) is assumed in all the simulation results presented in this 5.4.1.1 and 5.4.1.2.

5.4.1.1 Performance improvements and congestion avoidance

Corresponding experiments those analysed in 5.1.1 are repeated here using four and eight SBA sectors, 20s as the packet inter-arrival time and average results from the same five topologies. Two different transmitter power levels in OD mode are evaluated in *Dir*C-MAC: one uses maximum output power (the default configuration) and the other adjusts the output power to attain a similar range as C-MAC, and is indicated as LP (Low Power). The output power during directional transmissions is divided by G_t (four and eight here) with respect to the power used in the OD mode. The effect of the different configurations on the multi-hop routes is confirmed in Figure 5.13 where the distribution of the 100 nodes among hop distances from the sink is illustrated.

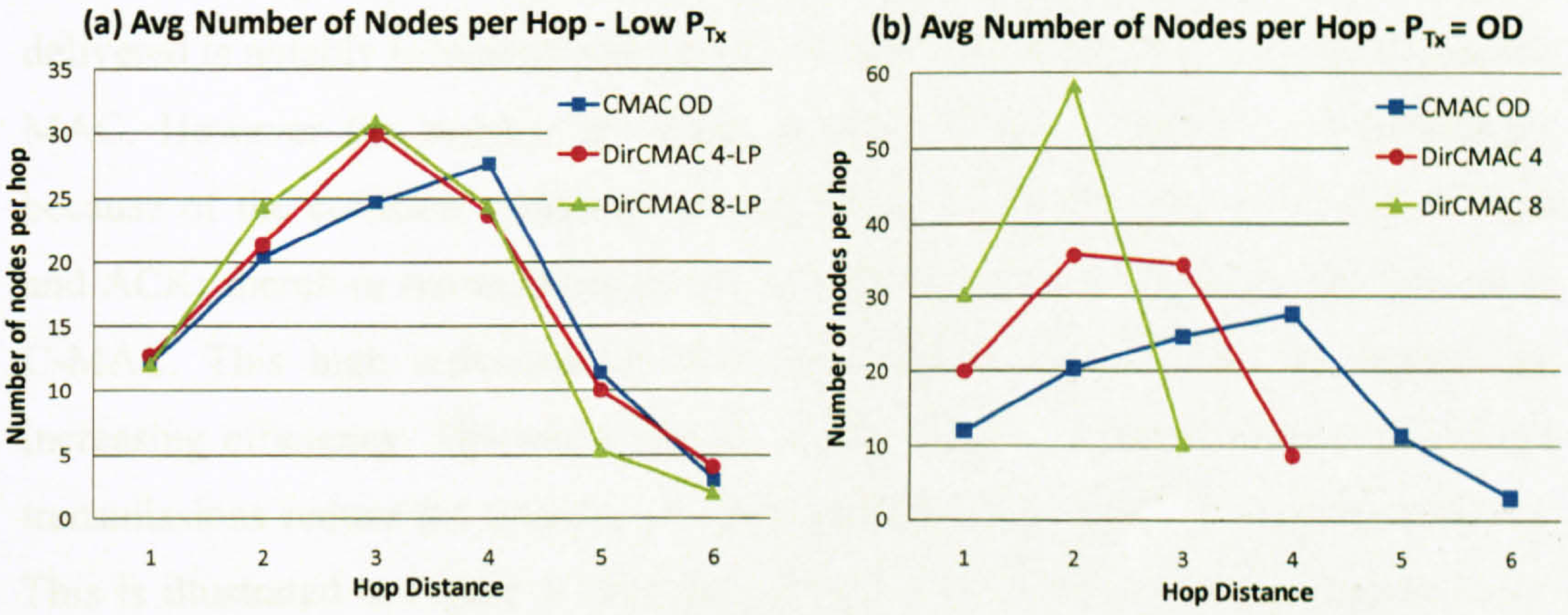


Figure 5.13 – Average number of nodes per hop in *Dir*C-MAC Vs C-MAC

Table 5.3 compares the simulation performance metrics of these five solutions. The duty-cycles have been adjusted to obtain over 90% of data delivery in every topology. The average results show the reduction of the mean number of hops towards the sink in *Dir*C-MAC. With lower communication hops, *Dir*C-MAC_4 and

*Dir*C-MAC_8 also achieve maximum performance in terms of lifetime and efficiency, which is more than double the C-MAC figures. Significant improvements are also obtained with the LP variants.

Table 5.3 - *Dir*C-MAC: Congestion and Performance Metrics

Metrics	CMAC OD	*Dir*CMAC 4-LP	*Dir*CMAC 8-LP	*Dir*CMAC 4	*Dir*CMAC 8
Duty-Cycle (%)	6.50	4.00	3.40	3.30	2.80
Mean Num Hops	3.08	3.03	3.01	2.33	1.80
Lifetime (days)	262.13	477.69	553.45	555.04	640.00
Efficiency (Pkts/mAs)	9.64	17.91	20.19	20.83	23.09
Avg. Collisions	7.11	4.76	3.73	8.30	9.59
Avg Re-Txon (%)	77.63	6.29	3.60	9.64	6.46
Ratio Tx/Rx time (%)	3.03	4.98	5.54	4.71	4.59
Ratio Idle/Rx time (%)	28.01	44.58	50.65	75.88	104.87
Battery Variation CV(%)	9.97	4.54	4.00	4.78	3.91

The drawback of an increased range in *Dir*C-MAC is shown in the congestion metrics such as the higher number of collisions and percentage of retransmissions. As a result, the control packets (RTS/CTS) sent in OD mode reach more neighbours in *Dir*C-MAC_4&8, and, consequently, the number of collisions per data packet delivered is notably increased with respect to the LP variant, and even higher than C-MAC. However the number of retransmissions is not increased correspondingly because of the collision avoidance enhancement with directional reception of Data and ACK; therefore retransmissions are reduced more than 10 times with respect to C-MAC. This high reduction of retransmissions is a key factor to explain the increasing efficiency. The major impact occurs close to the sinks where directional transmissions reduce the chances of data collisions even with high traffic intensity. This is illustrated in Figure 5.14(a) that compares retransmissions per hop of *Dir*C-MAC_LP and the OD C-MAC approach. Another direct consequence of the directional Data-ACK exchange is the reduction of overhearing packets shown in Figure 5.14(b).

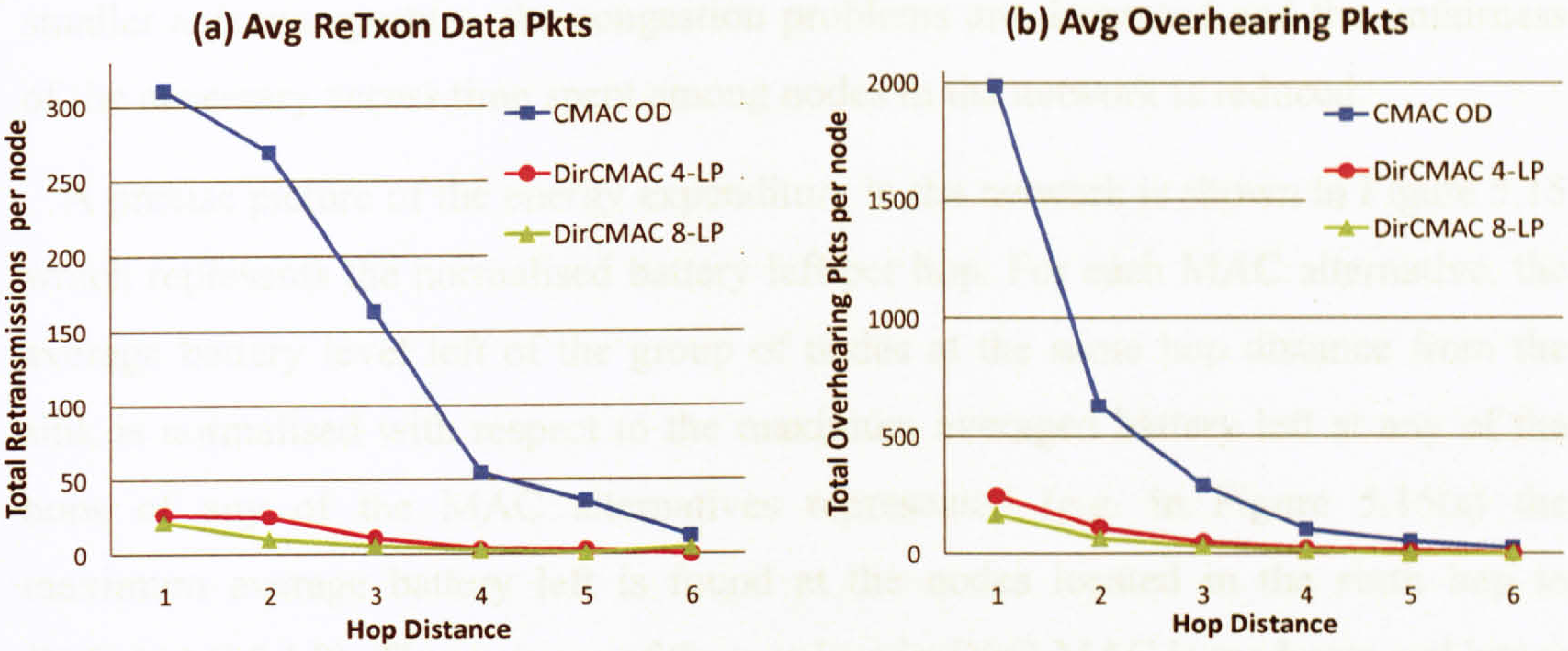


Figure 5.14 – Retransmissions and Overhearing: *Dir*C-MAC-LP Vs C-MAC

Furthermore, the improved management of the radio resources in *Dir*C-MAC is also demonstrated in the last three metrics of Table 5.3. With smaller duty-cycles, transmissions are more concentrated and the ratio Tx/Rx time is increased. Moreover, the time spent at the low power *Idle* state (a consequence of NAV scheduling) is particularly important. In parallel with the reduction in collisions caused by the higher range is the rising RTS/CTS overhearing at the network (amount of nodes undertaking NAV). This and previous trade-offs are better balanced with more sectors (higher SBA gain) and higher output power. The reduction of hops compensates the higher amount of collisions and, on average, a higher efficiency is obtained. Nevertheless, the primary advantage of *Dir*C-MAC with respect to C-MAC is the steering capacity. This is demonstrated with the already high efficiency obtained in the LP alternatives.

Finally, the last row of Table 5.3 represents the battery coefficient of variation[2] (CV) which is a meaningful metric to estimate the fairness of energy consumption among nodes in the network. It is shown that the battery CV is notably reduced with *Dir*C-MAC and smaller with increasing antenna directionality. With higher number of sectors, thus an increased ability to reduce Tx power and interferences with

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[2] CV is a well-known statistical metric that represents a normalised measure of dispersion of a probability distribution. It is defined as the ratio of the standard deviation (s) to the mean value ($\bar{x}$) (in percentage, CV = 100 · s/$\bar{x}$). It makes a big difference if s = 5 with a mean of $\bar{x}$ = 100, with a mean of $\bar{x}$ = 3. Relating the standard deviation to the mean resolves this problem.

smaller antenna aperture, the congestion problems are decreased and the unfairness of the necessary access time spent among nodes in the network is reduced.

A precise picture of the energy expenditure in the network is shown in Figure 5.15 which represents the normalised battery left per hop. For each MAC alternative, the average battery level left of the group of nodes at the same hop distance from the sink is normalised with respect to the maximum averaged battery left at any of the hops of any of the MAC alternatives represented (e.g. in Figure 5.15(a) the maximum average battery left is found at the nodes located in the sixth hop in *Dir*C-MAC 8-LP). The variance of these values in *Dir*C-MAC is moderate and hence the average network lifetime of Table 5.3 approximates the actual value per hop. Conversely, the significant divergence of power consumption appreciated in C-MAC due to the funnelling effect results in a significant practical lifetime reduction because as one-hop nodes start to die the sink becomes isolated.

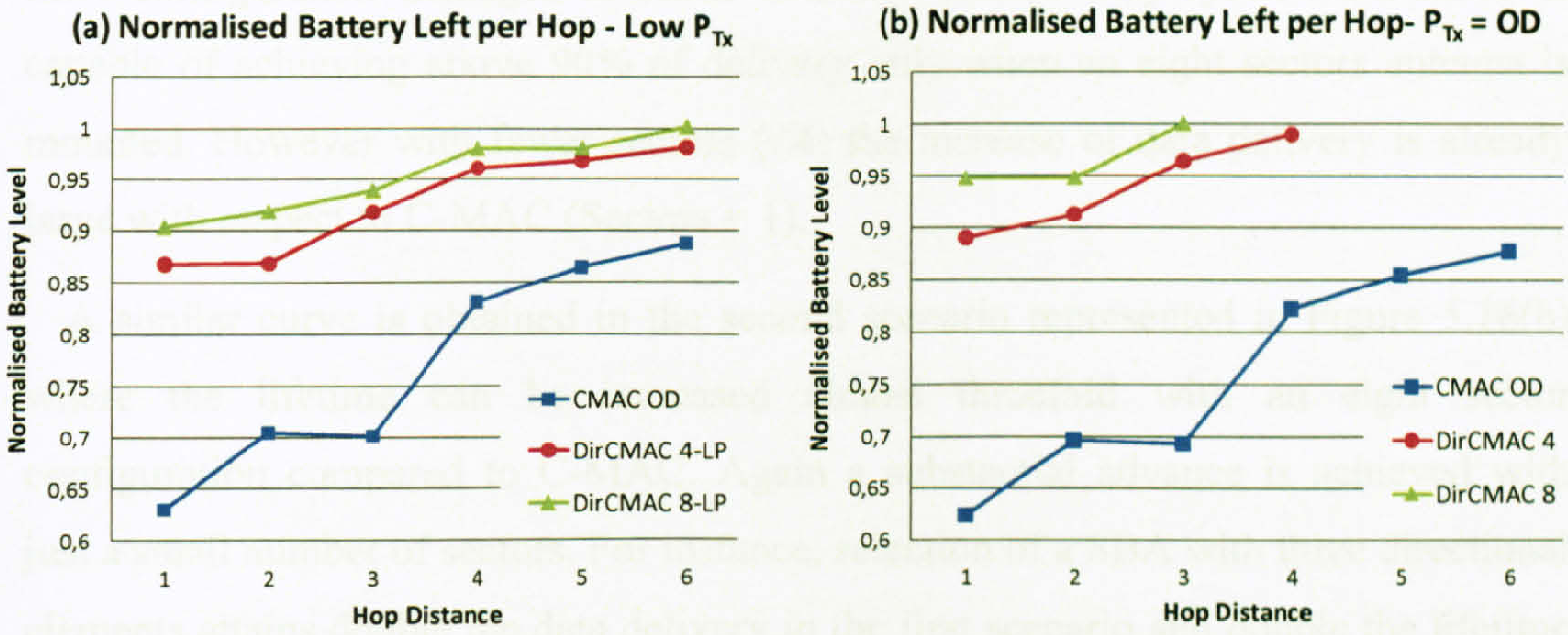


Figure 5.15 – Normalised Battery left per hop: *Dir*C-MAC Vs C-MAC

5.4.1.2 Performance expectancy with different sectorial antennas

The intention of this section is to assess the impact of the number of sectors of the switched beam antennas, in particular, from two to eight sectors have been considered. Regarding with current antenna technologies used in steerable SBAs, there is a limitation in the reduction of the effective antenna aperture of each of the directional elements that construct the antenna. For selection purposes, it results more realistic and affordable, in terms of the antenna size and cost, to deploy fewer sectors SBAs designed for WSN. For example, the MaxBeam [79] antenna can generate up to 15 directional beams by combining the four directional elements, but with an important limitation, a wide beamwidth, thus smaller gain, that is characteristic of each of the four directional elements. SBA design with a small antenna aperture in azimuth is a complicated task.

Two case studies are evaluated in the topology illustrated in Figure 5.1: first, the application requirement is to achieve a minimum lifetime (500 days) and a fixed duty-cycle is available for every configuration, and second, the requisite is to obtain over 90% of data-delivery at the sink regardless the energy used. A comparison of the performance of both cases is represented in Figure 5.16 for a different number of antenna sectors (*x*-axis). Simulations have duration of 2000s and the inter-packet arrival time is 20 seconds.

In the first scenario, Figure 5.16(a) shows the percentage of data delivery that each SBA configuration manages to reach with the limited duty-cycle. *Dir*C-MAC is capable of achieving above 90% of delivery only when an eight sectors antenna is mounted. However with fewer sectors (<4) the increase of data delivery is already large with respect to C-MAC (Sectors = 1).

A similar curve is obtained in the second scenario represented in Figure 5.16(b) where the lifetime can be increased almost threefold with an eight sector configuration compared to C-MAC. Again a substantial advance is achieved with just a small number of sectors. For instance, selection of a SBA with three directional elements attains double the data delivery in the first scenario and double the lifetime in the second.

More performance and congestion metrics for the different antenna types are collected in Table 5.4 where the highlighted metrics have been represented in Figure 5.16. Firstly the mean number of hops is considerable reduced with higher number of sectors and the maximum number of hops is half of those in C-MAC, with more than five sectors.

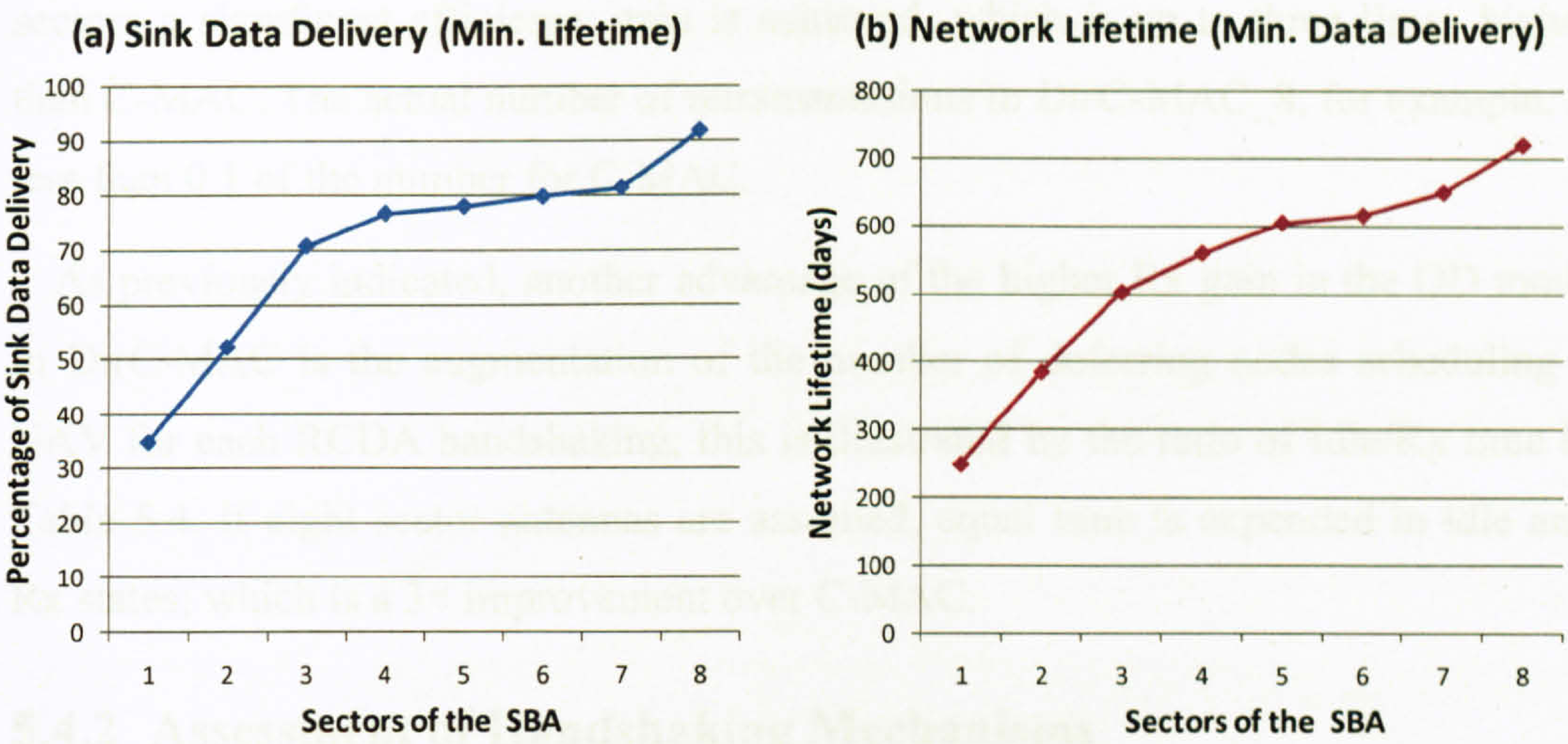


Figure 5.16 – *Dir*C-MAC with different requirements and SBA sectors

Table 5.4 - *Dir*C-MAC, Congestion and Performance Metrics with Two Application Requirements: Minimum Data Delivery of 90% and Minimum Lifetime of 500 days

SBA Sectors	OD	2	3	4	5	6	7	8
Mean Num Hops	3.11	3.27	2.74	2.48	2.21	2.07	2.05	1.88
Max Num Hops	6	6	5	4	4	3	3	3
Data Delivery Performance (Fixed duty-cycle 2,5% for Min. Lifetime 500 days)								
Data Delivery (%)	34.94	52.26	70.77	76.69	77.89	79.71	81.29	91.77
Efficiency	7.19	12.13	17.53	20.60	21.02	21.77	22.51	26.96
Lifetime (days)	514.47	580.24	619.23	671.57	674.62	682.79	692.42	719.52
Re-Txon (%)	73.22	36.14	16.30	14.20	9.59	9.51	8.78	5.92
Ratio Idle/RX (%)	28.62	40.57	51.63	66.25	72.16	83.16	89.04	97.46
Lifetime Performance (Variable duty-cycle, Min. Data Delivery 90%)								
Duty-Cycle	6.50	4.50	3.50	3.00	3.20	3.10	2.80	2.50
Efficiency	9.09	14.75	20.03	21.16	23.84	22.12	23.71	26.96
Lifetime (days)	250.33	386.14	502.88	558.89	604.44	615.52	649.06	719.52
Re-Txon (%)	82.38	46.18	16.22	15.20	9.51	9.47	8.77	5.92
Ratio Idle/RX (%)	28.62	40.57	51.63	66.25	72.16	83.16	89.04	97.46

Efficiency and lifetime are always increased with more sectors. Thus, in addition to the higher data delivery in the first scenario (Figure 5.16(a)), a much longer lifetime with respect to the minimum required (500 days) is obtained with sectorial antennas. As a result of the reduction in retransmissions with an increased number of sectors a significant efficiency gain is achieved, which is up to three times higher than C-MAC. The actual number of retransmissions in *Dir*C-MAC_8, for example, is less than 0.1 of the number for C-MAC.

As previously indicated, another advantage of the higher Rx gain in the OD mode in DirC-MAC is the augmentation of the number of deferring nodes scheduling a NAV for each RCDA handshaking; this is illustrated by the ratio of Idle/Rx time in Table 5.4. If eight sector antennas are assumed, equal time is expended in idle and Rx states; which is a 3× improvement over C-MAC.

5.4.2 Assessment of Handshaking Mechanisms

In order to qualitatively compare the handshaking mechanisms proposed in 5.3.2, the same scenario of Figure 5.16(a) is again simulated (a minimum lifetime of 500 days in the network topology of Figure 5.1); the simulation results are shown for the different contention mechanisms in the graph of Figure 5.17. A short duty-cycle is assigned to determine the amount of data at the sink that each solution is capable of delivering with the lifetime restriction. In Figure 5.17 the Inform Beacon (BDA) shows the best performance and a duty-cycle of 2.2% has been assumed in order to perceive incremental improvements up to the maximum percentage of data delivery obtained with the *InformBeacon_8* option. The beacon size assumed is equal to an RTS packet. Comparison of other important metrics is shown in Table 5.5.

With more than three sectors the Inform Beacon approach starts to dominate over the four-way handshaking (RCDA). A plausible reduction in the number of hops and an increase of the spatial reuse is needed to compensate for the high number of retransmissions in BDA. However, in contrast to the case of using RTS/CTS contention, the high number of retransmissions in BDA is not caused by collisions but is due to the many data packets which are sent when receivers are busy or in the Idle state. Without CTS, the increasing unawareness at the senders of the possible ongoing transmissions at their next-hop nodes exponentially augments the amount of retransmissions with respect to the *Dir*C-MAC solution.

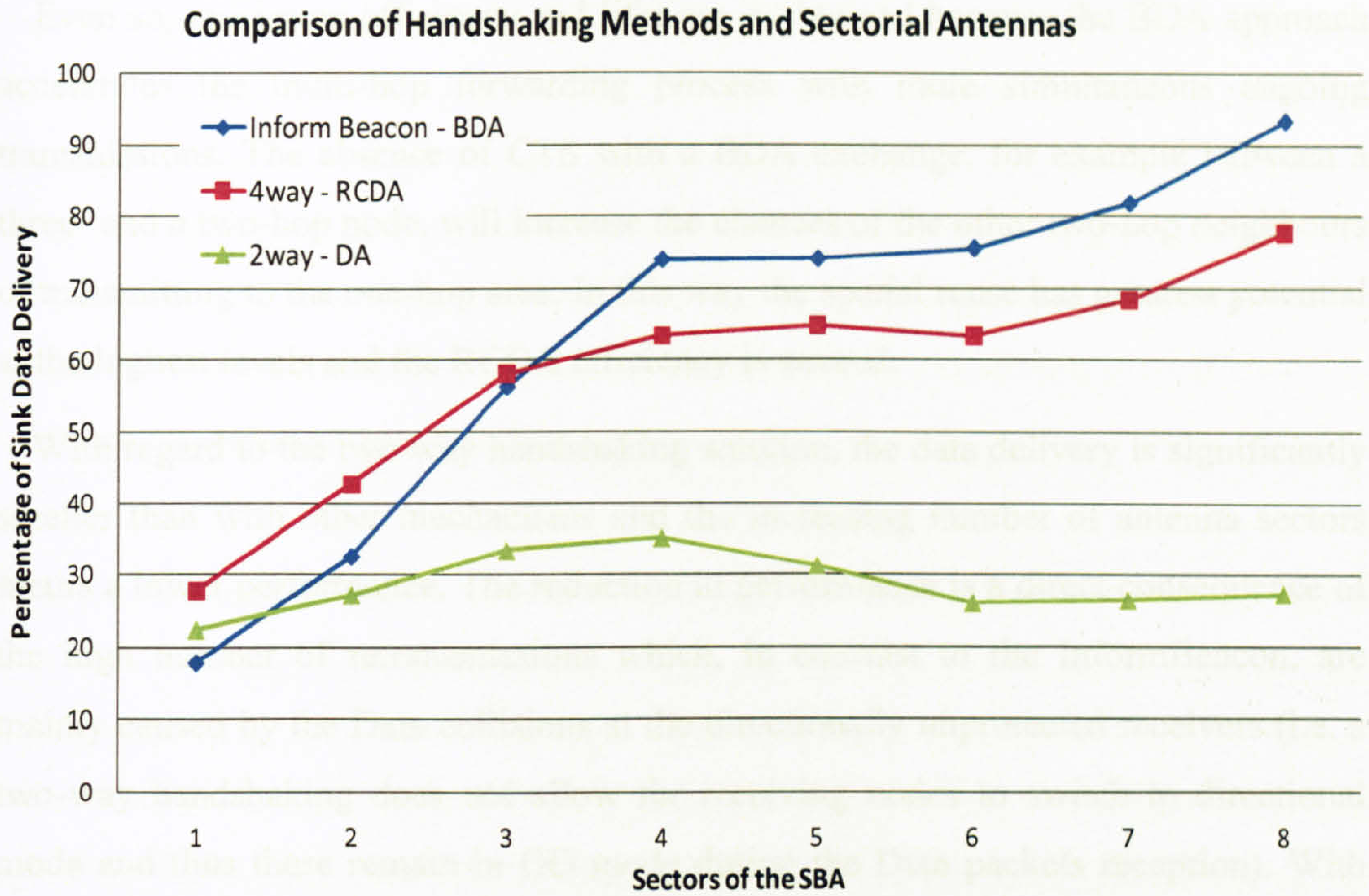


Figure 5.17 – Comparison of handshaking mechanisms with different SBAs

Table 5.5 – Comparison of Different Handshaking Mechanisms in *Dir*C-MAC: Congestion and Performance Metrics

SBA Sectors	OD	2	3	4	5	6	7	8
Mean Num Hops	3.11	3.27	2.74	2.48	2.21	2.07	2.05	1.88
Inform Beacon (BDA)								
Efficiency (Pkts/mAs)	3.72	7.27	14.16	19.00	21.20	22.09	25.27	30.66
Lifetime (days)	523.57	596.52	628.88	643.09	715.78	730.79	772.33	821.83
Re-Txon (%)	321.21	292.23	344.34	430.76	402.93	450.34	417.42	378.19
Ratio Idle/RX (%)	16.96	20.35	25.83	33.65	39.73	43.67	49.90	53.87
***Dir*C-MAC 4-Way Handshaking (RCDA)**								
Efficiency (Pkts/mAs)	6.48	10.75	15.60	17.22	19.41	18.74	20.53	24.11
Lifetime (days)	585.37	630.83	671.04	679.93	749.68	739.34	750.60	776.31
Re-Txon (%)	65.26	35.54	13.28	17.85	11.35	12.86	8.74	5.81
Ratio Idle/RX (%)	43.02	47.31	56.90	68.36	76.65	87.55	92.82	98.87
2-Way Handshaking (DA)								
Efficiency (Pkts/mAs)	4.03	4.58	5.27	5.37	4.87	3.54	4.28	4.70
Lifetime (days)	452.33	423.79	396.47	383.31	390.76	403.66	406.34	431.56
Re-Txon (%)	332.39	336.71	376.42	405.65	408.82	518.86	581.12	593.24
Ratio Idle/RX (%)	2.34	1.73	1.66	1.71	1.75	1.87	2.15	2.26

Even so, maximum efficiency and lifetime is obtained because the BDA approach accelerates the multi-hop forwarding process with more simultaneous ongoing transmissions. The absence of CTS with a BDA exchange, for example between a three- and a two-hop node, will increase the chances of the other two-hop neighbours of transmitting to the one-hop area. In this way the spatial reuse has greatest potential at the highest levels and the RCDA efficiency is exceed.

With regard to the two-way handshaking solution, the data delivery is significantly smaller than with other mechanisms and the increasing number of antenna sectors incurs a lower performance. The reduction in performance is a direct consequence of the high number of retransmissions which, in contrast to the InformBeacon, are mainly caused by the Data collisions at the directionally unprotected receivers (i.e. a two-way handshaking does not allow for receiving nodes to switch to directional mode and thus these remain in OD mode during the Data packets reception). With increasing SBA sectors, the higher OD Rx gain facilitates simultaneous reception of colliding Data packets in spite of the smaller antenna aperture of transmitting nodes. In addition the lack of RTS/CTS prevents the capacity of NAV scheduling which is represented by the low percentage of *Idle* state and the lower lifetime that is achieved.

Looking at the results in Figure 5.17 and Table 5.5, the overhead caused by control packets is well rewarded.

5.4.3 Comparison of Different MACs

With the aim of comparing previous contention-based directional solutions with a TDMA-based approach, the protocol LEACH with the assumptions explained in Section 4.3.1 has been simulated under the same conditions and topologies as *Dir*C-MAC. The solutions compared are:

- OD contention C-MAC,
- directional contention with 8 sectors and two types of handshaking, four-way handshaking (*Dir*C-MAC 8) and Inform Beacon (BDA), and
- LEACH with the cluster heads accessing the sink with two different mechanisms, CSMA and TDMA.

The duty-cycle of contention based solutions is 2% and the inter-packet arrival time is 20 seconds. The performance criteria are to provide at least a minimum lifetime of 500 days and a data delivery ratio as big as possible. The minimum lifetime limits the maximum duty-cycle of 2% in OD C-MAC that has been also used in the Inform Beacon 8 and *Dir*C-MAC 8. The lifetime requirement also restricts the available size of the forwarding period in LEACH (CSMA) where nodes have to compete (contention) to access the sink.

The metrics considered are the data delivery ratio at the sink, the average battery usage in the entire network (which is measured at the same instant, ¼ of lifetime in OD C-MAC) and the data acquisition delay at the sink. The average results from simulations in five random topologies (100 nodes and an area of 500m by 500m) have been normalised and visually represented in the bar chart of Figure 5.18. The amounts represented have been normalised to the maximum value obtained in any of the alternatives. Thus, a maximum data delivery (1≡95%), but also delay (1≡13,4s), is obtained with the idealistic LEACH (TDMA) and the highest battery usage (1≡26%) occurs in C-MAC.

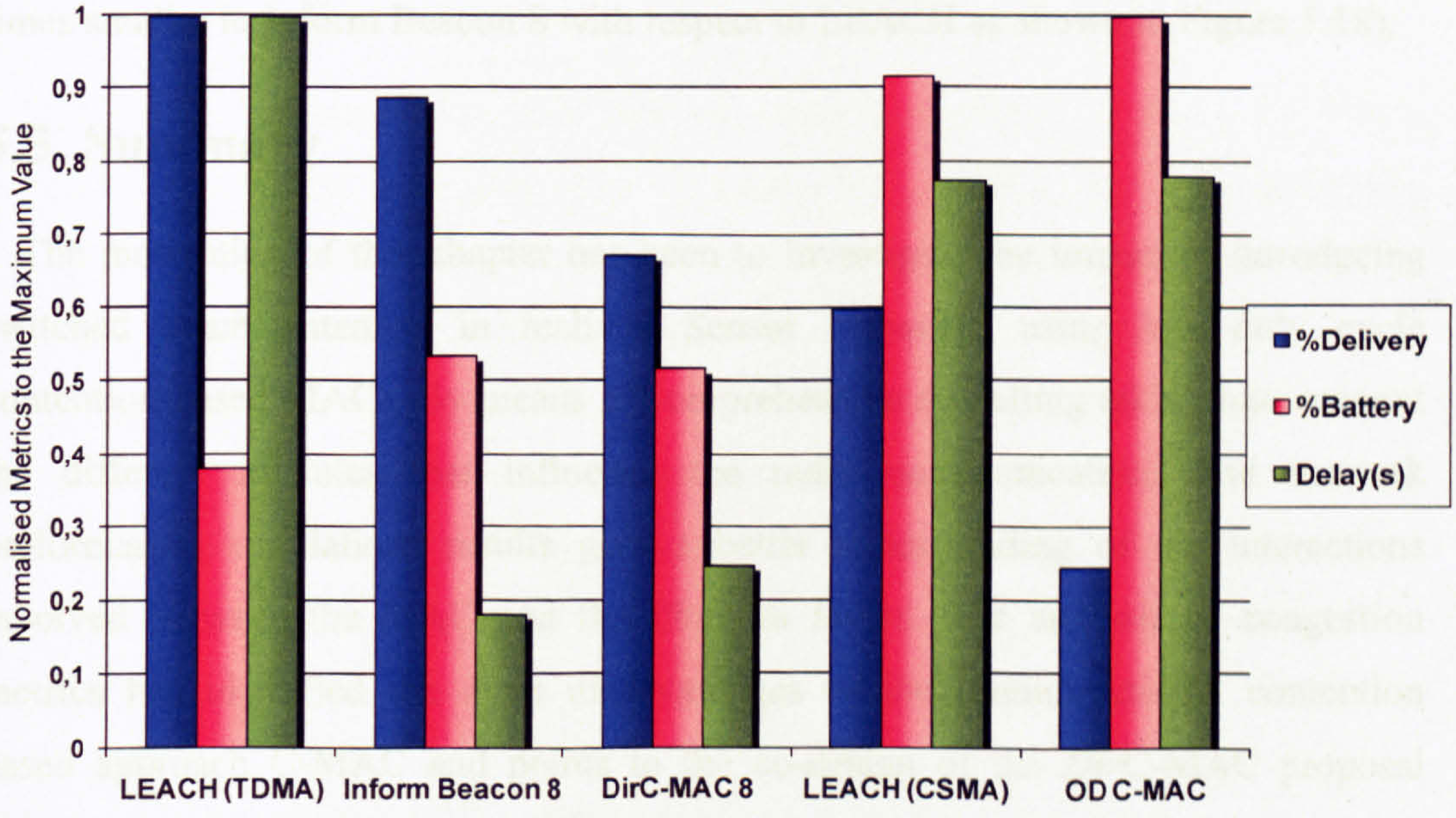


Figure 5.18 – Graphic comparison of different MACs

However, the results of LEACH when a CSMA contention mechanism is used during the forwarding period are notably deteriorated. CSMA does not prevent collisions at the sink because the network size considered enables the existence of hidden terminals. As a result the data delivery in LEACH (CSMA) is even smaller compared to *Dir*C-MAC 8 while the battery usage is 45% higher with respect to this directional contention solution.

On the other hand, with a TDMA approach, the cluster-heads have different slots assigned. With a collision-free access and perfect synchronisation, the percentage of data delivery is maximised in LEACH (TDMA). In addition, with the absence of a contention period where cluster-heads compete to access the sink, the energy consumption is remarkably decreased in the TDMA approach. In this manner LEACH achieves higher performance than the *Dir*C-MAC solutions with eight sectors. However the need of a high power Tx mode, CDMA channelisation, tight synchronisation in addition to the other considerations previously commented, makes LEACH a less attractive solution. Nevertheless improvements of the directional solutions with respect to C-MAC are patent, without losing the advantages of contention MACs as scalability, adaptation to network dynamics and lower delay (6 times smaller in Inform Beacon 8 with respect to LEACH as shown in Figure 5.18),

5.5 Summary

The motivation of this chapter has been to investigate the impact of introducing switched beam antennas in realistic Sensor Networks using low duty cycle contention-based MACs. By means of comprehensive modelling taking into account the different modules that influence the radio communications and network performance, simulations results give a better understanding of the interactions involved between the MAC and the Physical layers. The analysis of congestion metrics has identified the main disadvantages of the omnidirectional contention based approach C-MAC and points to the co-design of the *Dir*C-MAC proposal using directional antennas.

Performance evaluation of the architecture model shows a positive impact resulting from the introduction of directional antennas, with the main improvements occurring in data delivery and power consumption. The performance modelling adopted illustrates via simulation the dependency of the MAC performance on radio channel characteristics, transceiver operation and antenna radiation pattern assumptions. Consistently increasing the number of sectors on the switched beam antennas obtain higher efficiency in addition to the trade-off resulting from a higher gain with major impact on the OD receiving mode. Nevertheless efficiency and lifetime of C-MAC has been outperformed by more than three times using directional antennas. Comparison of the results for default and low power (LP) *Dir*C-MAC, indicate that the main cause of the performance enhancement is the reduction of congestion problems with directional Data-ACK exchange and also, where appropriate, the reduction in the number of communication hops.

Analysis of the results comparing different handshaking techniques on *Dir*C-MAC gives a better understanding of the tradeoffs obtained with directional transmissions, especially between throughput improvements due to spatial reuse and power reduction attributable to the higher *Idle* state with increasing amount of NAV scheduled. Among the different schemes, the Inform beacon solution compensates better the previous tradeoffs showing an enhanced data delivery performance with similar power consumption with respect to the four-way handshaking mechanism.

In spite of the significant reduction of congestion problems along the whole network, the inherent funnelling effect of nodes-to-sink applications is considerable in *Dir*C-MAC. Even with directional communications, the contention access mechanism is limited with higher traffic intensity, with the maximum impact occurring at the one-hop nodes. Chapter 6 investigates the adoption of hybrid MAC techniques in order to minimise the congestion problems closer to the sinks. The idea of using directional antennas is not abandoned and switched beam antennas are proposed to be placed on the network sinks, but not in every node of the network.

Chapter 6

Adaptive Hybrid MAC Design: SSAS

The communication protocol presented in this chapter within XLCA represents a general cross-layer Application-Routing-MAC-PHY approach, which is the principal contribution of this thesis. SSAS, Scheduled Sectorial Access at Sink, is an adaptive hybrid localised sink-oriented Routing/MAC protocol that integrates C-MAC as base link access mechanism.

The underlying motivation of designing SSAS, as with *Dir*C-MAC, is to improve the communications efficiency on contention based systems through modifications at the MAC level that reduce the impact of congestion. However different strategies characterise each solution. In the previous presented *Dir*C-MAC, the MAC-PHY co-design focuses on altering every point-to-point contention exchange with the introduction of directional transmissions, aiming to increase the resistance against collisions. This adaptation on the link layer results in higher network performance with respect to C-MAC.

In contrast, SSAS concentrates on the overall co-design of a communications solution for multi-hop nodes-to-sinks applications. Accounting for the escalating traffic and the non-uniformity of congestion throughout the network, SSAS has been conceived to reduce the impact of the funnelling effect close to the sinks by the adoption of scheduled access techniques. The objective is to increase responsibility and functionality of the sinks to control the access from its neighbours and to adapt the network operation if the application requirements are violated under unpredicted events. The establishment of clusters during the initialisation permits the sinks to coordinate their one-hop nodes, which acquire a slave role.

The strength of SSAS is based on the scheduled access at the sink and the enhancement of the number of one-hop neighbours of the sink achieved by increasing the communication range with switched beam antennas. Figure 6.1 shows the higher size of the cluster using four sectors with respect to the OD alternative. Each of the sectors (1 to 4) in Figure 6.1 represents the coverage area of the different switched beams radiated by the sink's SBA. A higher number of sectors and beam gain, which increases the range of the sink, is very desirable, firstly because more one-hop nodes can benefit from the collision-free TDMA access and, secondly, the increase of one-hop nodes and the area that these occupy facilitates the channel spatial reuse at the two-hop nodes and the traffic intensity is spread in more links with reduced probability of congestion problems.

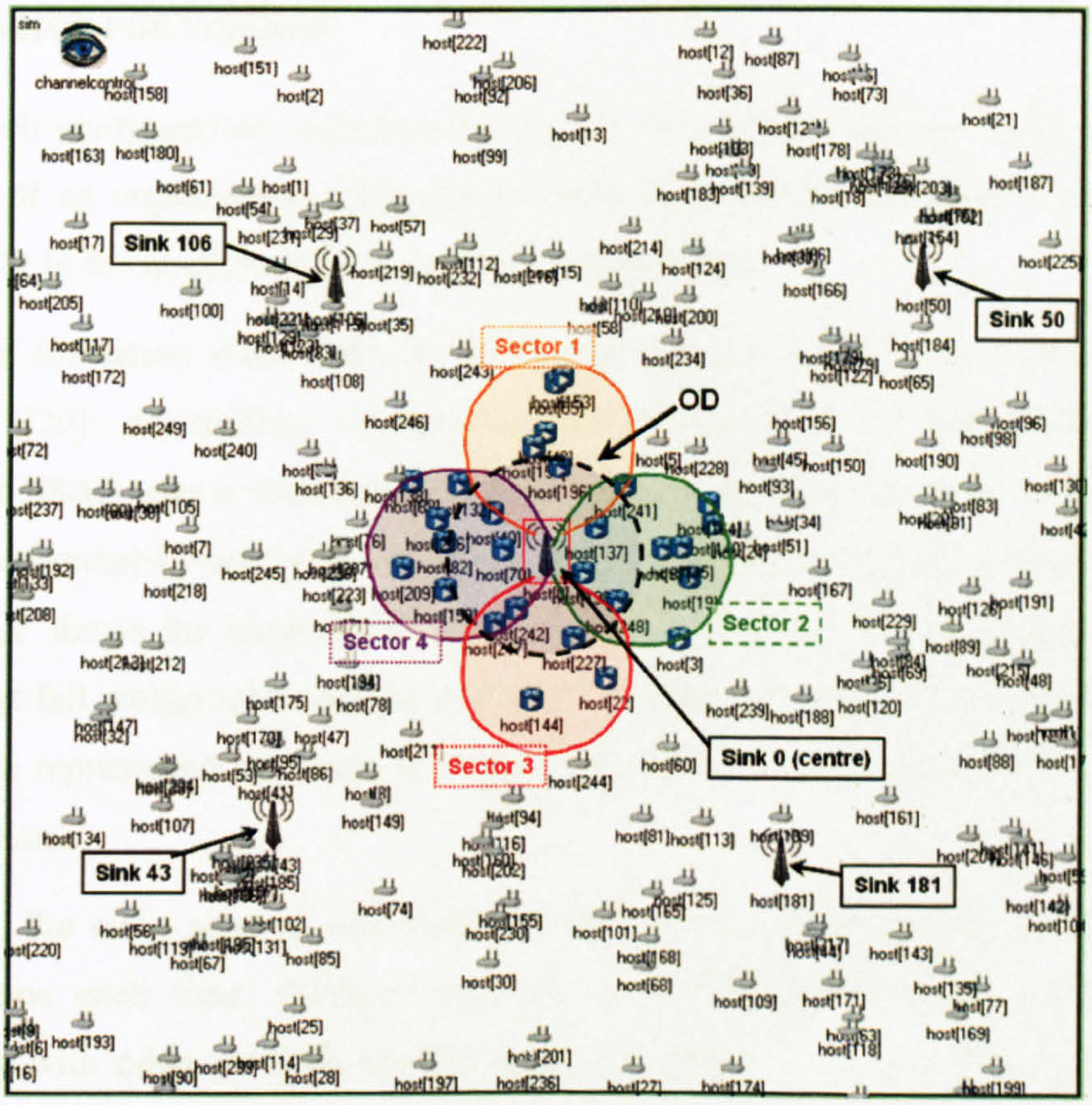


Figure 6.1 - Cluster size with OD and 4 sectors (750mx750m, 250nodes)

Nevertheless, with the one-hop nodes acting as sinks (only Rx) during the wake periods, the probability of accessing the channel at the two-hop nodes is notably increased compared to the pure-contention C-MAC where both, one- and two-hop nodes, compete to forward their packets. The beneficial effect of the high reduction of congestion spreads to the rest of the network, with much faster data delivery towards the one-hop nodes, the effectiveness of the contention access is increased and smaller duty-cycles can be employed. As a result, SSAS achieves significant performance improvements compared to the pure contention-based alternatives (C-MAC), *Dir*C-MAC, B-MAC and LEACH.

SSAS has been implemented inside the XLCA platform; the functionality required in the cluster formation, and hybrid access operation is explained in the sections 6.1 and 6.2.

6.1 SSAS Initialisation: Cluster Formation and Synchronisation

The self-configuration initialisation period is restructured in SSAS with the addition of an organisation stage that enables the formation of clusters around the sinks prior to the neighbour discovery and routing phase.

Cluster formation with sinks in SSAS has similar stages to the ones used in LEACH [29]: advertising, application and transmission of scheduling tables. However SSAS uses a sectored approach where sinks associate with their one-hop nodes on a sector-by-sector basis, resulting in *n* (number of sectors) virtual clusters. Figure 6.1 shows the coverage of each of the four sectors (1-4) and identifies the nodes that fall within each sectorial cluster. The different steps of the initialisation in SSAS are represented in Figure 6.2 when the sink mounts a four sectors switched beam antenna.

Firstly, the sinks send an advertisement packet towards each sector, re-directing the antenna each time. Random backoffs and CSMA are carried out to avoid collisions with other possible nearby sinks transmissions. If any node receives an advertisement from different sectors or from other sinks, it selects the sector and/or sink with the highest advertisement packet signal strength. Secondly, the one-hop nodes that have received the advertisement send an application packet to the sink at the time specified in the advertisement packet plus a delay dependent on the nodes' unique ID, thus avoiding possible collisions. This technique becomes necessary because as *n*, and thus the directional gain, increases the sector range of the sink's antenna can be large enough that nodes inside the coverage area cannot detect (CSMA) transmissions from other nodes inside this sector. After reception of the applications packets, the sinks generate and send one different scheduling table packet (Figure 6.2 (b)) towards every sector to inform every applicant one-hop node of its slot position, the initial fixed slot time and the time remaining for the next forwarding period (*FWD* in Figure 6.2 (a)).

Afterwards, analogous to the initialisation phase in XLCA, the sinks start the sequential forwarding routing algorithm to spread application requirements and configuration parameters. The cluster formation (slot assignment) enables the one-hop neighbours to start the broadcast of the routing packet in a coordinated way (see Routing stage in Figure 6.2 (b)). Timing of the different stages is dependent of the number of antenna sectors used at the sinks and it is represented at the bottom of Figure 6.2 (b). With the packet sizes that have been indicated in Table 4.1 the time required for the cluster formation is negligible in comparison to the time needed in the Routing stage. As indicated in Section 4.1.2, the imposition of delays during the sequential forwarding of the routing packets is necessary to maximise the detection of neighbours and increase the accuracy of the routing decisions.

Although initialisation can be repeated if the network requirements change, maintenance of the network synchronisation, as a result of adaptation to network dynamics, is approached with several adaptive techniques in SSAS. Apart from the re-routing and Adaptive Sleeping schemes that have been introduced into the architecture (XLCA) in Chapter 4 , other characteristics of SSAS are explained in the Section 6.2.

6.2 SSAS Operation: Hybrid MAC and Adaptive Schemes

In essence, SSAS is based on C-MAC and assumes the same contention techniques that have been described in 4.1.4: CSMA, four-way handshaking (RCDA), ARQ and NAV. Hence, C-MAC is used to deliver the packets during the active time to the one-hop nodes, which act like sinks receiving and buffering the packets. What differs in SSAS from CMAC is the forwarding period in which the Data packets are received from the one-hop nodes in an orderly fashion.

At the start of the forwarding period, the one-hop nodes wait to receive the scheduling table (ST) packet, which contains the time information necessary for the scheduled access (Figure 6.3). The slot sizes are a multiple of the size of a Data packet. The sink allocates different slot sizes to the one-hop nodes depending on the number of Data packets that are expected from each node. The sink keeps track of the number of packets that are received in each frame from every one-hop node. This information is stored and updated in the sink cluster one-hop table, which is shown in Figure 6.3, and is used by the *Adaptive Slot* scheme to adapt the slot allocation as explained in 0.

Consecutively to the reception of the ST packet, the one-hop nodes switch to *Idle* state and wake up to send their buffered packets in a burst to the sink in the specific slot assigned. In fact, the sink notifies with the ST packet (Figure 6.3) that the node in sector n with slot position k_n needs to set a timer of $Time[n][k]$ before transmitting data. The slot size is calculated as $Time[n][k+1] - Time[n][k]$. The slots positions and sizes are updated at every frame with the ST packet as indicated in Figure 6.2 (a). Consequently, one-hop nodes do not require tight synchronisation since the ST packet is transmitted just before each forwarding period.

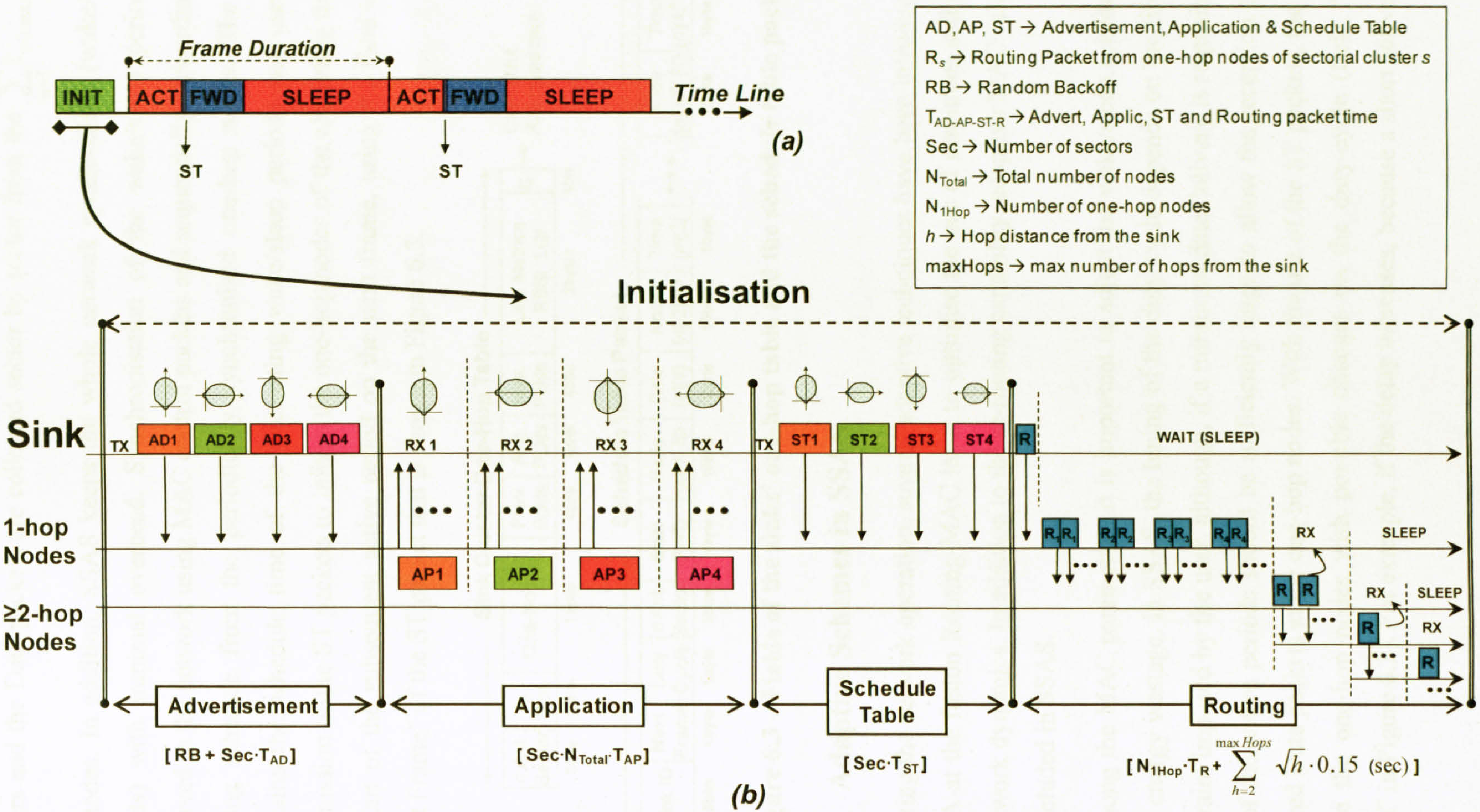


Figure 6.2 - Time Line States (a). Initialization Stages, Sink's cluster formation and Routing (b)

If the sink mounts a SBA, a different ST packet is sent to each of the n sectorial clusters and the Data packets are collected sector by sector from the $\sum_{n=1}^{Sec} k_{n(\max)}$ one-hop nodes. In addition, SSAS keeps the whole network synchronised (wake/sleep periods) with minimal overhead. Synchronisation of the wake/sleep periods is preserved in the network using MAC control packets and sequentially forwarding the sleeping schedule from the periodically synchronised one-hop nodes. The sink maintains the schedule time of the alternating wake/sleep periods and uses the transmission of the ST packets to inform the one-hop nodes of the remaining time to the start of the subsequent active period on the next frame, using the field called "Next Frame" of the ST packet that is shown in Figure 6.3.

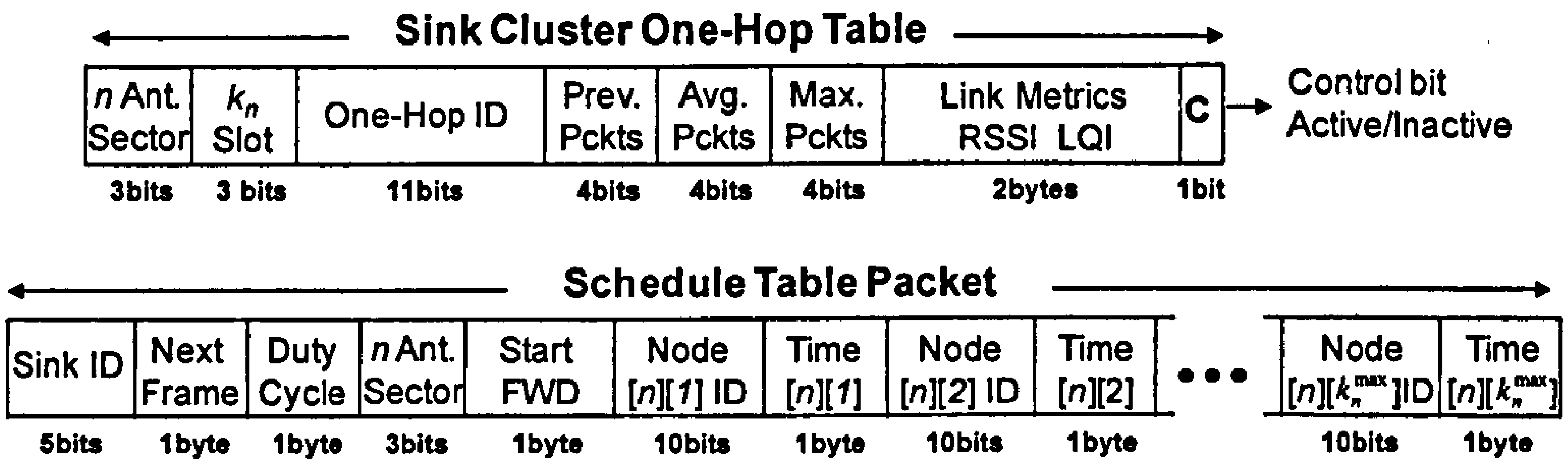


Figure 6.3 – Fields of the sinks' one-hop table and the schedule table packet

6.2.1 Adaptive Schemes in SSAS

During the network operation, several adaptive techniques have been introduced in XLCA at the fusion Routing-MAC layer to optimise the use of resources and adapt to network dynamics. In addition to the re-routing capability, adaptive MAC schemes are included in SSAS.

Among the MAC parameters, it is important to adjust the wake/sleep schedule to avoid energy wastage. In SSAS, the tuning of the duty cycle depends on the lifetime constraint imposed by the user, although, if a minimum data delivery is requisite, the size of the active periods should be sufficiently large to allow the reception of the required Data packets at the one-hop nodes. With the use of the ST packets, the sinks update the one-hop nodes with possible changes on the duty-cycle (field "Duty Cycle" in Figure 6.3). For example, if the delay increases, because a short active time impedes data packets arriving in the same frame in which they have been generated, the sink can instruct a duty-cycle increase to guarantee the desired delay. Instructions are spread to the rest of the nodes in a sequential forwarding process within MAC control packets (CTS or ACK).

Additional adaptive features have been considered in SSAS for security monitoring applications (e.g. seismic monitoring or intruder detection) in order to react and adjust the network operation in the event of alarms (time-critical data). The alarm packets are sent with highest preference and thus are routed before other type of packets towards the one-hop nodes. When alarms reach the sink in the forwarding period, the sink can order to increase the duty-cycle and/or reduce the frame duration if the acquisition delay of the alarm events is higher than the specified by the user.

Moreover, the *Adaptive Sleeping* scheme locally adjusts the duty-cycle of each node to the current traffic conditions. With the incorporation of sinks' sectorial clusters and the hybrid MAC access at the one-hop nodes, the *Adaptive Sleeping* proposed in C-MAC (Section 4.1.5.2) has been adapted to the needs of the SSAS protocol. In addition, a new adaptive scheme, the *Adaptive Slot*, is included to optimise the slot assignment within the cluster.

6.2.2 Adaptive Sleeping at One-Hop Nodes

Whereas the traffic load varies extensively within the network, the *Adaptive Sleeping* in C-MAC and SSAS entails significant energy savings in the whole network. However, the role of one-hop nodes in SSAS (acting like sinks) leads to modifications in the *Adaptive Sleeping* scheme illustrated in Figure 6.4.

In SSAS, among the one-hop relay nodes some of them do not have two-hop neighbours, a situation that is more likely to happen when the antenna gain is increased (a higher number of sectors is used). These nodes can remain sleeping during the active period and only wake up to deliver their own data packets to the sink during the forwarding period (third *if* (C_2) in Figure 6.4(a)). Note that the existence of these backup nodes in SSAS can increase the network resilience to extend the connectivity time of one-hop neighbourhood to the sink, thus the network lifetime.

```
Adaptive Sleeping implementation (MAC Layer)

a) Start Active Time
  if ( currentFrame > trainingFrames ) //$C_1$
      if ( No Pkts to Send || ImOneHop )
          if ( No Further Neighbours || Im Not Next Hop )//$C_2$
              GoToSleep()
          else
              schedule ( $3 \cdot timeout / hop2sink$, sleep )
b) After Reception of ACK (DATA SENT) Only hop2sink>1
  if ( $C_1$ & No Pkts to Send )
      if ( $C_2$ )
          GoToSleep()
      else if ( $RX\text{-}PKTS \geq AVG\text{-}PKTS$ ) //$C_3$
          schedule ( $timeout / hop2sink$, sleep )
      else
          schedule ( $3 \cdot timeout / hop2sink$, sleep )
c) One-Hop Nodes After Tx of ACK (DATA RECEIVED)
  if ( ImOneHop )
      if ( $C_1$ & $C_3$ )
          schedule ( timeout, sleep )
      else
          schedule ( $3 \cdot timeout$, sleep )

 Note: $timeout = 10\% \cdot ActiveTime$
```

Figure 6.4 - The pseudo-code for the Adaptive Sleeping in SSAS

Additionally, once the traffic patterns become steady after the "warm-up" interval (training period C_1), one-hop nodes that have received the expected number of packets (C_3), measured and updated during previous frames, can schedule a *timeout* (Figure 6.4(c)): if during this time the node is not contacted by any two-hop sender it goes into a sleep mode until the forwarding period. Finally, the hybrid MAC allows the sinks to remain sleeping during the active contention period, which entails a longer sinks' lifetime with respect to C-MAC.

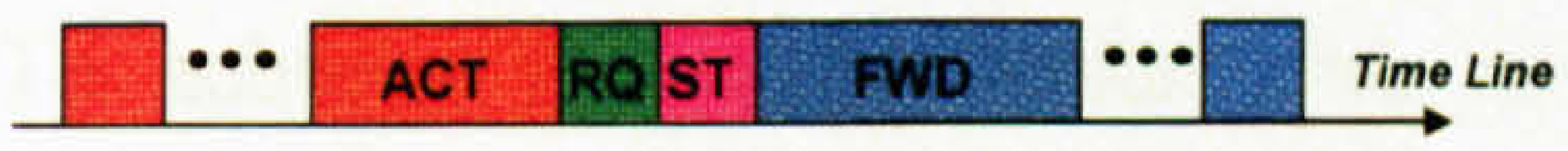
6.2.3 Adaptive Slot

Adaptive Slot is a mechanism that enables the adjustment of the sinks' slots assignment depending on the traffic requirements of the one-hop nodes. Initially a fixed slot size (*FixedSlot* in Figure 6.5(b)) is assigned to every node depending on the network size and expected traffic.

Nonetheless, the maximum buffer size restricts the maximum slot assigned. However, as previously mentioned, some one-hop nodes do not forward more than their own data packets while others, depending on the antenna type and topology, need to forward many more packets.

If the network remains static and traffic generation is constant it is likely that the number of packets received at one-hop nodes will fluctuate below a maximum value. The sink keeps a record of the packets received inside the sink cluster one-hop table (Figure 6.3). Hence sinks adapt the slot assignment to each node after some training frames (see Figure 6.5(c)). Consequently, the delay and the battery consumed by the sinks are reduced. In addition, provision is made in each sector for nodes that have experienced a significant increase of packets received (e.g. as a result of a one-hop node failure) to demand a slot augmentation, which will be included in the scheduling. This is made during the Request (RQ) period as shown in Figure 6.5(a).

Adaptive Slot implementation (MAC Layer)



```
a) Request Extra Slots (RQ=Sectors·2ms) to be included in the ST
    if (currentPkts > MaxPktsSent)
        schedule ( MySector · 2ms + RB, sendRQ )

b) After Receive Schedule Table (ST)
Read ST:
get PrevSlots & MySlot=n & SlotsB4Me[n] (when SlotID[n]=MyID)

    if ( currentFrame < trainingFrames ) // Fixed Slot, $C_1$
        schedule ((PrevSlots + MySlot) · FixedSlot , FWD )
    else // Adaptive Slot, $C_2$
        schedule ((PrevSlots+SlotsB4Me+MySlot)·$T_{DATA}$ , FWD )

c) Schedule Table Formation (Sink)
    PrevSlots = 0
    for s=0 to s=(Sectors-1)
        if (s>0 )
            if ( $C_1$ ) PrevSlots = Nodes of Previous Sector [s-1]
  LOOP      if ( $C_2$ ) PrevSlots = Total Slots in Previous Sector [s-1]
        SlotsB4Me[0] = PrevSlots
        for n=1 to n=(num nodes of sector s)
            SlotID[n-1] = NodeID[s][n]
            SlotsB4Me[n] = SlotsB4Me[n-1] + NumPkts [NodeID[s][n]]

    SEND ST [s] (PrevSlots, Vector SlotID, Vector SlotsB4Me)
```

Figure 6.5 - The pseudo-code for the Adaptive Slot

6.3 Performance Evaluation

An extensive evaluation using simulations has been conducted to compare the improvements of SSAS with respect to other alternatives such as C-MAC, *Dir*C-MAC, B-MAC and LEACH for typical monitoring applications. Depending on the type of antenna mounted on the sink, three configurations are evaluated in SSAS: SSAS OD (omnidirectional antenna), SSAS_4 (four sectors SBA) and SSAS_8 (eight sectors SBA. The impact of different network metrics is analysed in a wide range of different scenarios.

6.3.1 Considerations for the MACs Assessment

The general application requirements are to maximise the network lifetime while assuring high data delivery rate (>90% if achievable) and fairness from every network node. In addition, the packet delivery should be smaller than the packet inter-arrival time (time between which a sensing data packet is generated at every node in the network). To achieve this delay constraint, an inter-frame duration (Figure 6.2 (a)) smaller than the inter-arrival time is considered.

When a minimum data delivery is imposed, meaningful metrics such as network lifetime expectancy (in days) and energy-efficiency are used to assess the performance of each protocol. The efficiency is measured as, on average, the number of packets that are delivered to the sinks using a battery unit (mA/s) in the whole network. With the radio as main source of energy consumption, maximising network lifetime is equivalent to target maximum efficiency on the communications protocol design. However, in contention based MACs, a reduction of the radio awake time is limited by congestion problems if a high data delivery is required in multi-hop nodes-to-sink applications. The solutions *Dir*C-MAC and SSAS are co-designed to reduce these problems, although it is shown in the simulation results analysed in 6.3.3 that the impact of congestion on the network performance considerably differs in these two protocols.

Explanation on the LEACH and B-MAC design assumptions is necessary to understand the performance simulation results in the different scenarios proposed.

The description of the implementation of these two MACs inside the XLCA platform and the design parameters assumed can be found in Section 4.3.

This chapter concentrates on the evaluation of the different solutions during normal network operation, using the shortest distance routing trees provided by the initialisation period. Hence, adaptation of the re-routing scheme to varying congestion conditions or node failures is not considered here; rather it is considered in Chapter 7 with respect to other proactive schemes. However, the use of MAC adaptive schemes is assumed in SSAS and C-MAC. In particular, the use of *Adaptive Sleeping* implemented in both, SSAS and C-MAC, has a major impact and enables a doubling of the average network lifetime in large networks when for example 250 nodes (Figure 6.1) are considered. The network lifetime is measured as the time after which half of the network nodes have completely depleted their batteries. Additionally, the *Adaptive Slot* scheme in SSAS reduces by 20% in SSAS OD the delay and battery used at the sink; greater improvements are obtained if more sectors are considered (SSAS_4 and SSAS_8). Moreover, the sinks in SSAS only need to be awake during the forwarding period and, as a result, their battery usage is notably reduced. For example, in the network of Figure 6.1, the SSAS mechanism leads to two and three times higher sink lifetime compared to LEACH and C-MAC respectively. The benefits of the hybrid MAC and adaptive schemes in SSAS are repeated under the different scenarios analysed in this section, although, the results analysed concentrate on comparing the overall network efficiency and lifetime among the different protocols.

The simulation results have been averaged from five or ten seeds that generate different random topologies with the condition that a full-connected graph is formed, i.e. any node have at least one neighbour and one routing tree to reach the sink. The variation among performance results at each topology is dependent on the specific metric being considered, however the coefficient of variation (CV), (CV= $100 \cdot Deviation_{Standard}/Mean$), see footnote number 2 in 5.4.1.1, is consistently lower than a 10% for the key metrics evaluated such as data delivery, battery level or delay.

6.3.2 Congestion Avoidance with SSAS

The main improvement of the SSAS protocol over other CSMA-based well-known protocols, e.g. scheduled contention S-MAC (similar to C-MAC) or channel-polling B-MAC, is its ability to reduce congestion in the network. With the optimistic assumption that LEACH employs TDMA for the intra-cluster and point-to-sink communications (as indicated in Section 4.3), LEACH only suffers from congestion problems during the clusters formation, those are minimal. With the idealistic assumptions (Section 4.3) of perfect synchronisation and high range to reach the sink from any point in the network, LEACH allows TDMA one-hop communications from any node in the network towards the sink. Hence LEACH is scaled to larger networks with the associated cost of a greater number of slots allocated and higher energy consumption in the sink. In addition inter-cluster interference is avoided with the use of CDMA. For this reason, LEACH is not included in the comparisons of this section.

With the aim of assessing the capacity of the hybrid MAC to decrease congestion problems in comparison to the based contention C-MAC, three different evaluation scenarios, and diverse performance metrics are evaluated. In these scenarios, SSAS OD is used because it provides the same routing and number of nodes per hop with respect to C-MAC.

6.3.2.1 Impact of the hybrid MAC at one-hop nodes

Corresponding experiments to those analysed in 5.1.1 have been repeated using SSAS OD in the same five topologies with an area of 500m by 500m, 100 nodes, simulation time of 4000s, a minimum of 90% of data delivery and packet inter-arrival times of 20s and 100s. Table 6.1 compares the key design and performance metrics for C-MAC and SSAS.

A relevant improvement in SSAS is the ability to reduce the duty-cycle, which results in a higher efficiency and lifetime with respect to C-MAC, which is more significant when the data rate increases. Without contention access at one-hop nodes, the funnelling effect is mitigated and the accessibility from two-hop nodes is notably increased. As a direct consequence, the percentage of retransmissions in SSAS is significantly reduced, almost by half, with respect to C-MAC. However, this reduction is not homogeneously distributed throughout the network.

Table 6.1 - Design Metrics and Overall Network Performance

	Frame Size (sec)	Duty-Cycle(%)	Lifetime (days)	Efficiency (Pkts/mAs)	Delay (sec)	ReTxon (%)
CMAC_20s	10.00	6.00	262.13	9.64	14.80	77.63
CMAC_100s	25.00	1.50	1103.32	7.85	50.10	70.03
SSAS OD_20s	10.00	1.00	906.62	34.68	12.23	42.25
SSAS OD_100s	25.00	0.50	1312.91	9.84	33.02	33.90

The average number of retransmissions and, the average ratio of retransmitted packets per packets delivered by the nodes located at the different six hops from the sink, are represented in Figure 6.6(a) and Figure 6.6(b) respectively. In these figures, the impact of congestion (retransmissions) within the network and the effect of the SSAS hybrid MAC are appreciated.

Being collision-free, the TDMA access at the one-hop nodes reduces to zero the amount of Data retransmissions in SSAS which, for instance, is higher than 300 with CMAC in Figure 6.6(a) due to the funnelling effect close to the sink. In SSAS, with one-hop nodes acting as sinks, the probability of the two-hop nodes of accessing the one-hop neighbourhood is increased.

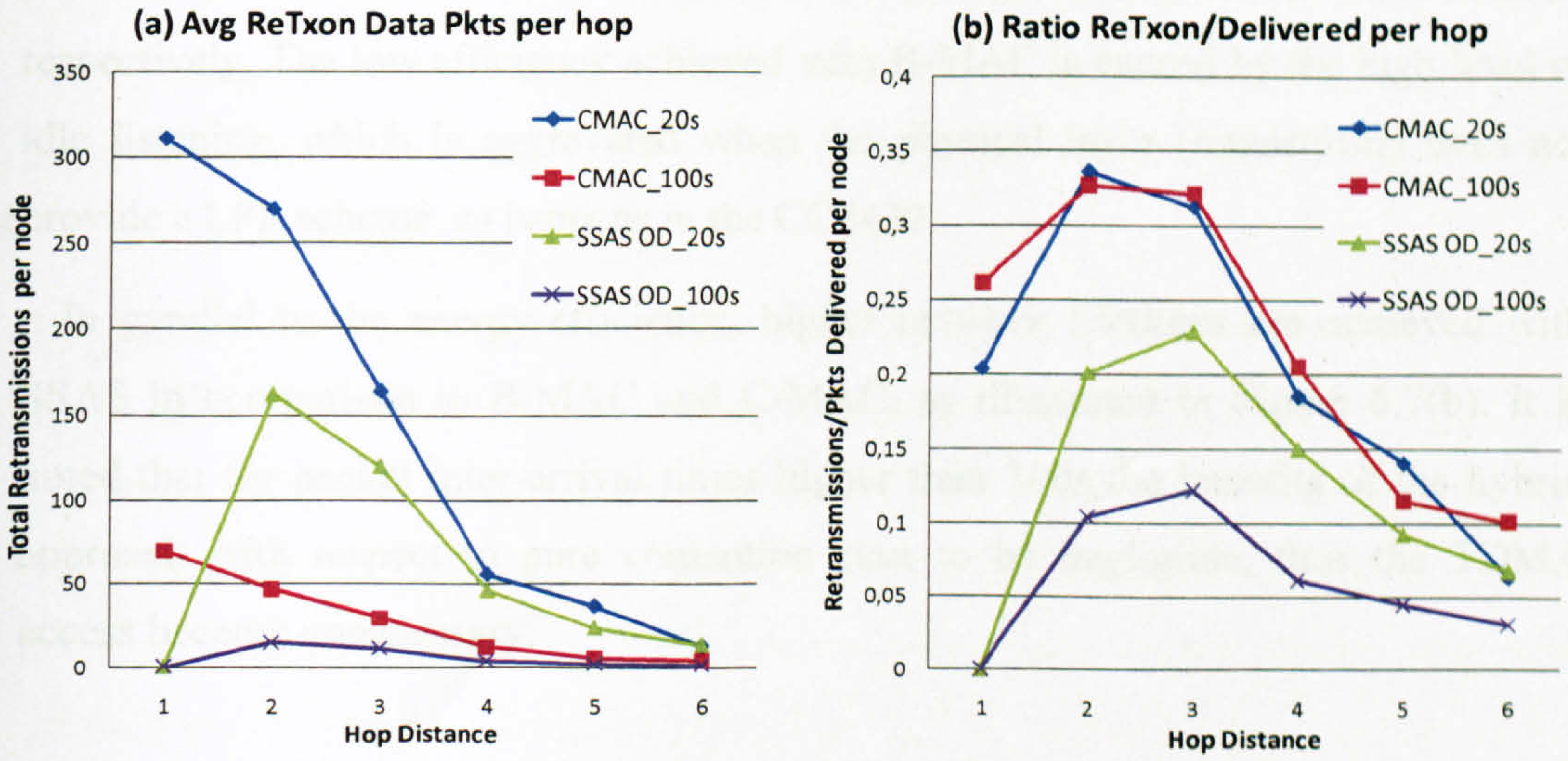


Figure 6.6 - Retransmissions per hop in SSAS (OD) Vs C-MAC

The reduction of congestion is spread towards further hops and, as a result, the Data packets arrive faster to the one-hop area, which entails smaller delays at the network and the capacity of decreasing the duty-cycles, as shown in Table 6.1.

6.3.2.2 Permanence of SSAS capacity at lower data rates

The energy efficiency values shown in Table 6.1 indicate that higher data rates incur higher efficiency in SSAS. However, throughput is not the primary requirement in numerous monitoring WSN applications that assume low sampling rates of sensing measurements. When the amount of traffic decreases, the benefits of a hybrid approach may result negligible with respect to the base contention solution. In order to measure the significance of the hybrid MAC, SSAS OD is compared here with the pure-contention C-MAC and the polling protocol B-MAC with low data rates.

The same five random topologies assumed in 6.3.2.1 have been simulated using SSAS, C-MAC and B-MAC with the packet inter-arrival time varying from 20 to 400s. To reduce more the traffic load it is assumed that only 25 of the 100 nodes generate data packets (sources) and the rest act as relay nodes. The impact of the data rate on the lifetime and energy efficiency of these MACs is compared in Figure 6.7(a) and Figure 6.7(b) respectively. Significantly higher energy efficiency is obtained with SSAS in comparison to C-MAC and B-MAC, especially as the data rate is increased (smaller packet inter-arrival time). With a packet inter-arrival time of 20s, SSAS results ten and three times more efficient than B-MAC and C-MAC respectively. The low efficiency achieved with B-MAC is caused by the high level of idle listening, which is aggravated when the physical layer (transceiver) does not provide a LPL scheme, as happens in the CC2420.

In parallel to the energy-efficiency, higher network lifetimes are achieved with SSAS in comparison to B-MAC and C-MAC, as illustrated in Figure 6.7(b). It is noted that for packet inter-arrival times higher than 300s the benefits of the hybrid approach with respect to pure contention start to be negligible, thus the TDMA access become unnecessary.

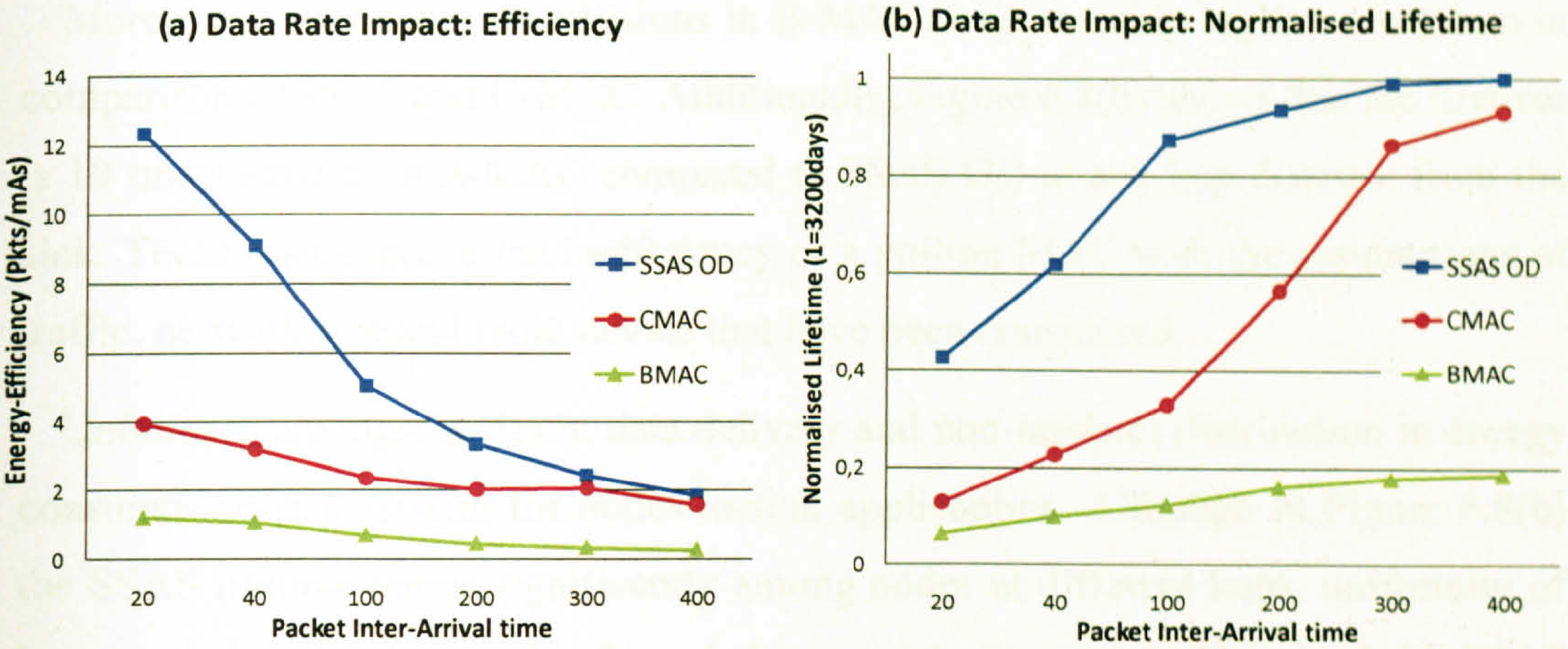


Figure 6.7 – Lifetime and Efficiency with low data rates (*n*=100, 25sources)

Furthermore, higher network efficiencies that those shown in Figure 6.7(a) can be obtained with SSAS if more nodes and elevated data rates are considered or, if directional antennas are mounted in the sink. For example, with a packet inter-arrival time of 20s and a network of 500 nodes (all sources), the solution SSAS_8 achieves an energy-efficiency of 125 Pkts/mAs, which is 10 times higher than the one obtained SSAS OD_20s in Figure 6.7(a).

6.3.2.3 Per-hop case study: inequality on network metrics

Performance evaluation of SSAS, C-MAC and B-MAC has been carried out by means of network simulations of the particular network topology of Figure 6.1, using the sink 0, 250 sources, packet inter-arrival time of 20s, and a simulation time of 4000s. The number of collisions and the expected lifetime of the nodes located at the eight hop distances are represented in Figure 6.8(a) and Figure 6.8(b), respectively.

Figure 6.8(a) shows a high reduction in collisions using SSAS OD, which reflects the reduction of the funnelling effect when the one-hop nodes do not compete to access the sink during the active periods. Consequently, the congestion level at one-hop nodes in SSAS is highly alleviated reducing the number of collisions more than five times compared to C-MAC. The beneficial effect is spread towards the further hop nodes and SSAS achieves, in the entire network, up to a three times higher node lifetime with respect to C-MAC in Figure 6.8(b).

Moreover, the amount of collisions in B-MAC is appreciably higher at any hop in comparison to SSAS and C-MAC. Additionally, Figure 6.8(b) shows that the lifetime is 10 times smaller in B-MAC compared to SSAS OD at any hop distance from the sink. These results prove the inefficiency of a polling MAC with the assumptions of traffic, network size and radio device that have been considered.

Unfairness amongst nodes in data delivery and non-uniform distribution in energy consumption is persistent for nodes-to-sink applications. Although in Figure 6.8(b) the SSAS lifetime varies significantly among nodes at different hops, uniformity of battery drain distribution in the whole network is notably increased in SSAS achieving a coefficient of variation (CV) amongst all nodes of 8% against 21% (C-MAC) and 63% (B-MAC). However, an analysis of the particular battery levels of each node confirms the existence of energy-vulnerable nodes in any of the solutions considered, although, it is less significant in SSAS. For example, in the results of this section, at the end of the 4000s of simulation, the difference between the minimum battery left (an energy-vulnerable two-hop node) and the maximum battery left (an energy-saver seven-hop node) is of 42% and 69% in SSAS and C-MAC respectively. This inequality of energy consumption causes some nodes to die well before the average expected lifetime, which considerably limits the network operational time due that energy-vulnerable nodes are usually located close to the sinks. Chapter 7 proposes proactive solutions in SSAS to extend the lifetime of the most vulnerable nodes.

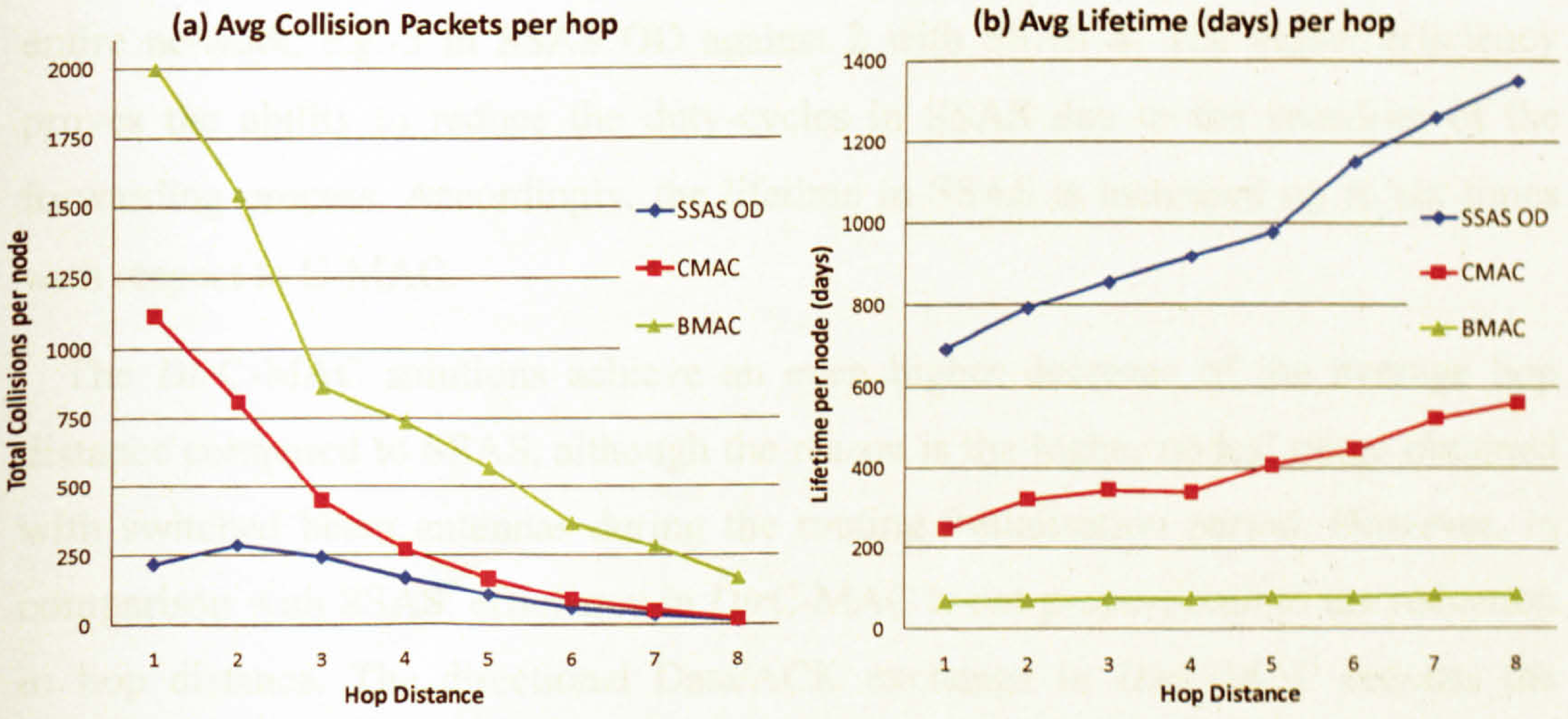


Figure 6.8 – Collisions and Lifetime per hop: *n* = 250 (Figure 6.1)

6.3.3 *Dir*C-MAC Vs SSAS

The advantage of a sink-localised hybrid MAC in SSAS with respect to a generalised directional contention in *Dir*C-MAC has been demonstrated under several network scenarios and user requirements. As an example, Table 6.2 compares key metrics for the C-MAC, *Dir*C-MAC and SSAS solutions extracted from network simulations of 100 nodes (500m by 500m) and a packet inter-arrival time of 20s. The duty-cycles have been again selected to obtain at least 90% of data delivery rate at the sink.

Table 6.2 - Metrics Comparison: C-MAC, *Dir*C-MAC & SSAS

	CMAC OD	DirC-MAC4	DirC-MAC8	SSAS OD	SSAS_4	SSAS_8
Duty-Cycle	5.00	3.50	2.80	1.50	0.80	0.50
Avg Hops	3.15	2.30	1.78	3.15	2.56	2.03
Efficiency	13.88	20.21	26.61	41.59	68.58	100.00
Lifetime (days)	305.53	450.57	615.94	864.18	1406.69	2057.71
Re-Txon (%)	83.01	13.91	10.15	34.49	19.20	10.56
Collisions/ Delivered (%)	10.56	12.53	19.25	2.95	2.27	1.51
EI (K=100)	1.26	1.41	1.96	2.90	4.20	5.56

The energy-efficiency results (normalised to the maximum achieved with SSAS_8) demonstrate the improvements of the hybrid approach and the benefits of enlarge the cluster size (TDMA access) with more sectors in the sink's SBA. This is reflectedwith the reduction of the average number of hops towards the sink in the entire network, e.g. 3 in SSAS OD against 2 with SSAS_8. The higher efficiency proves the ability to reduce the duty-cycles in SSAS due to the speed-up of the forwarding process. Accordingly, the lifetime in SSAS is increased up to six times with respect to C-MAC.

The *Dir*C-MAC solutions achieve an even higher decrease of the average hop distance compared to SSAS, although the reason is the higher nodes' range obtained with switched beam antennas during the routing initialisation period. However, in comparison with SSAS, efficiency in *Dir*C-MAC is not proportional to the reduction in hop distance. The directional Data/ACK exchange in *Dir*C-MAC reduces the impact of congestion but the funnelling effect is not as minimised as it is in SSAS.

Nevertheless, the improvements of *Dir*C-MAC solutions with respect to C-MAC are also noticeable, with double efficiency obtained if an eight sectors SBA is mounted in every node. A decreasing amount of multi-hop communications and enhanced collision avoidance permit the reduction of the percentage of retransmitted packets (Data) to even lower values than those in SSAS as shown in Table 6.2. However, *Dir*C-MAC also suffers from the congestion problems of C-MAC due to the saturated contention access to the sinks. In comparison to the SSAS scheduled access to the sinks, the inefficiency of a pure contention access is illustrated with the ratio of collisions per packet delivered, which is even higher in *Dir*C-MAC than in C-MAC because of the higher Rx gain of the SBAs that has been explained in Chapter 5. A high number of collisions limits the channel accessibility and forces the protocol to increase the shared active time to deliver all the network packets towards the sink. On the other hand, SSAS attains collision-free TDMA access at the sink avoiding the congestion problems and extensively increasing the protocol efficiency. For instance, the energy-efficiency of SSAS_8 is seven times higher than the one obtained with C-MAC.

An interesting value that illustrates the profitability of the active time by the different solutions is the Efficiency Index (EI). The EI represents the ratio of the power used in Tx and Idle (during NAV scheduling) states compared to the one used in Rx (reception of packets + *idle listening*) and switching states. This index is calculated as

$$EI = K \cdot \frac{w_{Tx} \cdot T_{Tx}(t) + w_{Idle} \cdot T_{Idle}(t)}{w_{Rx} \cdot T_{Rx}(t) + w_{Switch} \cdot T_{Switch}(t)} \tag{5}$$

where $T_{Tx}(t)$, $T_{Rx}(t)$, $T_{Idle}(t)$ and $T_{Switch}(t)$ are the accumulated time of the Transmit (Tx), Receive (Rx), Idle and Switching modes in period *t*, respectively; D_c is the duty cycle; w_{Tx}, w_{Rx}, w_{Idle} and w_{Switch} are the normalised or absolute power consumption per time unit for Tx, Rx, idle and switching modes, respectively; K is a constant scaling factor. Note that the switching time corresponds to the transition stages between the different CC2420 radio transceiver states represented in Figure 4.7. The power consumption during switching time is equal to the mean power between transition states. Considering that during the active time these transitions are made between *Tx*, *Rx* and *Idle* state, the value of the power consumed during switching is equal to $w_{Switch} = \frac{1}{3}(w_{Tx} + w_{Rx} + w_{Idle})$. Table 6.2 shows the impact of the hybrid approach and also the directional antennas increasing the EI, being more than four times higher in SSAS_8 than in C-MAC.

Ideally a SSAS solution based on *Dir*C-MAC instead of C-MAC will allow improved performance, thus energy-efficiency, enhancing current SSAS with higher cluster sizes due to the nodes' antenna gain and the reduction in collisions (retransmissions) due to the limited nodes' antenna aperture.

6.3.4 Impact of Network Size

Observation of the previous SSAS results in 6.3.3 emphasises the impact of the sink antenna range, thus the size of the one-hop area, in increasing the network performance. In order to evaluate how this effect is reduced in larger deployments, simulation results at multi-size topologies have been investigated. In addition to C-MAC, the TDMA-based protocol LEACH with the assumptions explained in Section 4.3.1 is also compared here with the SSAS solutions.

Five different configurations that maintain the same density of nodes are considered: 100, 150, 200, 250 and 300 nodes uniformly distributed, in an area of 500m by 500m, 610m by 610m, 700m by 700m, 790m by 790m and 866m by 866m respectively. In all the configurations one sink is placed in the centre of the deployment area. However, for LEACH, in the 200, 250 and 300 nodes configurations, two sinks are required to achieve full connectivity of the network. The two sinks are placed equidistant in the diagonal joining the NW and SE vertices of the area. The packet inter-arrival time is 20s and the frame duration 10s. Duty-cycles are adjusted so the maximum data delivery is achieved but idle listening is minimised (further reduced if adaptive sleeping is used). With these assumptions, the impact of the network size in SSAS, LEACH and C-MAC is represented in terms of network lifetime and energy-efficiency in Figure 6.9 and Figure 6.10 respectively.

Figure 6.9 shows the normalised network life with respect to the maximum lifetime, which is 2057 days and is obtained with SSAS_8 (8 sectors used). For every configuration the SSASs alternatives and LEACH manage to achieve more than 90% of data delivery; whereas C-MAC only reaches this amount if less than 250 nodes are considered.

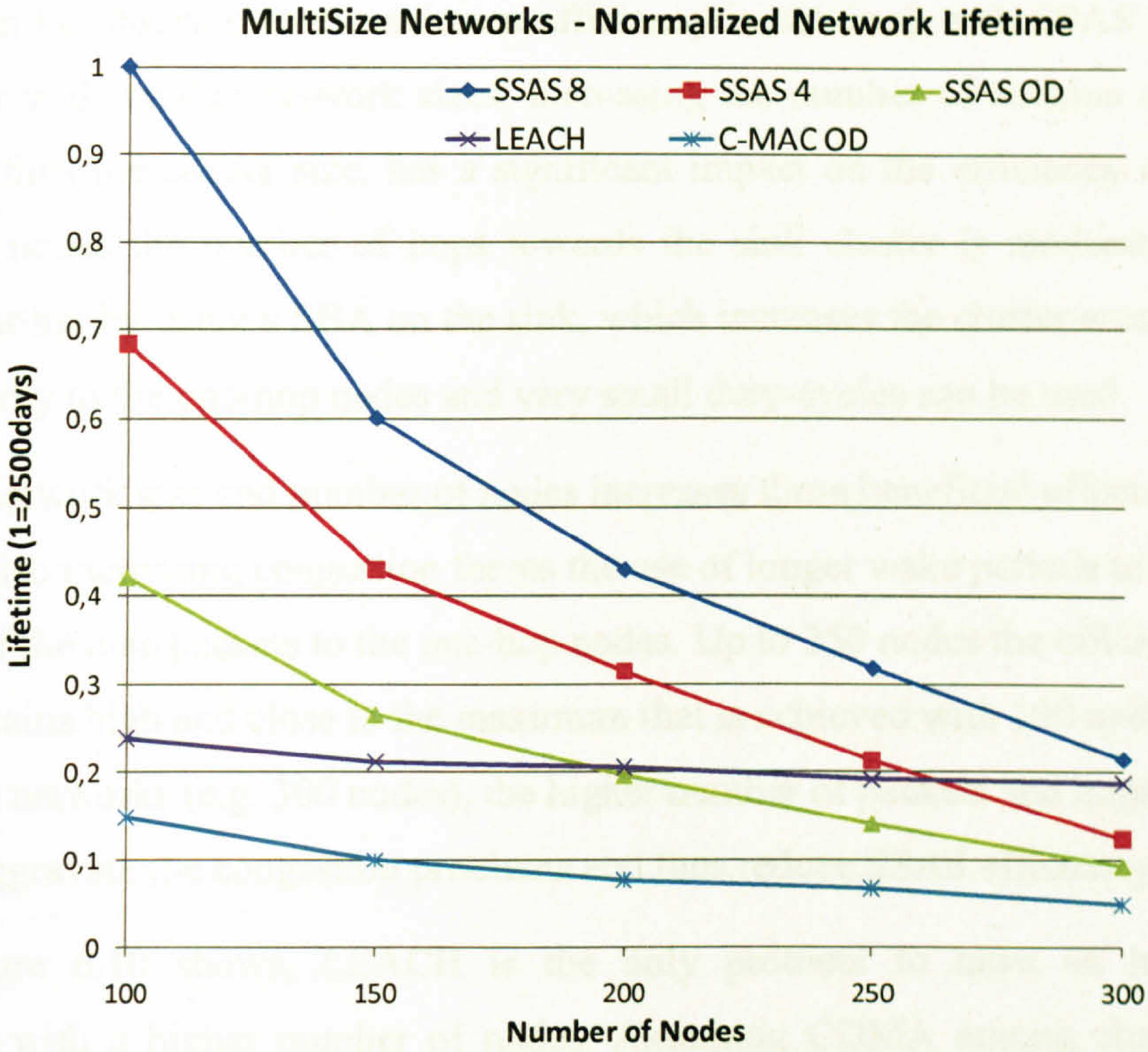


Figure 6.9 – Impact of network size (=density) in the network Lifetime

The impact of congestion in C-MAC is very significant for larger networks, when the traffic towards the sink increases. In networks with more than 200 nodes it can be observed that when using the pure contention C-MAC a state of congestion collapse [106] is reached after which, under increasing traffic transit (number of nodes), less data will be delivered to the sinks with the same amount of energy. Thus the network wastes energy sending packets from the edges towards the sinks that would be lost from collisions or buffer overflow. In this situation, increasing the duty-cycle does not improve the performance. In the simulations, the duty-cycles for C-MAC are approximately adjusted to the congestion collapse point in order to deliver the maximum number of packets to the sink but avoid energy wastage. With this configuration, the network lifetime in C-MAC remains almost constant, as shown in

Figure 6.9, but significantly inferior to the lifetime achieved with SSAS (always 5 times smaller than SSAS-8).

Figure 6.10 illustrates the energy efficiency in terms of packets delivered at the sink. It can be observed that maximum efficiency is obtained with SSAS solutions and higher with smaller network sizes. Increasing the number of antenna sectors at the sinks, thus the cluster size, has a significant impact on the efficiency of SSAS. With 100 nodes the number of hops towards the sink cluster is moderate, and is reduced further by using a SBA on the sink, which increases the cluster area: packets arrive rapidly to the one-hop nodes and very small duty-cycles can be used.

As the network size and number of nodes increases these beneficial effects are reduced; also increasing congestion forces the use of longer wake periods to ensure delivery of the data packets to the one-hop nodes. Up to 250 nodes the efficiency of SSAS remains high and close to the maximum that is achieved with 100 nodes. In larger size networks (e.g. 300 nodes), the higher number of packets and hops towards the sink aggravate the congestion problems and thus reduce SSAS efficiency.

As Figure 6.10 shows, LEACH is the only protocol to have an increasing efficiency with a higher number of nodes. Assuming CDMA among clusters and TDMA access from nodes to sinks, the only possible problems in LEACH can be collisions among cluster head and/or applicants during the cluster formation, which is very low. In addition, LEACH parameters (introduced in 4.3.1), thus duty-cycle, are the same for all the configurations. Note that with equal density the cluster sizes in LEACH are likely to be similar with any network size. With higher data delivery at the sink but comparable energy usage among nodes in the network explains the increasing efficiency with higher network sizes. However, the efficiency of the co-designed SSAS solution with eight sectors of the antenna used always outperforms LEACH performance. It is noted that when the point-to-sink access method is CSMA (as shown in the MACs comparison of Section 5.4.3), LEACH capacity decreases significantly due to the high contention time required at nodes throughout the network to send their packets successfully to the sink.

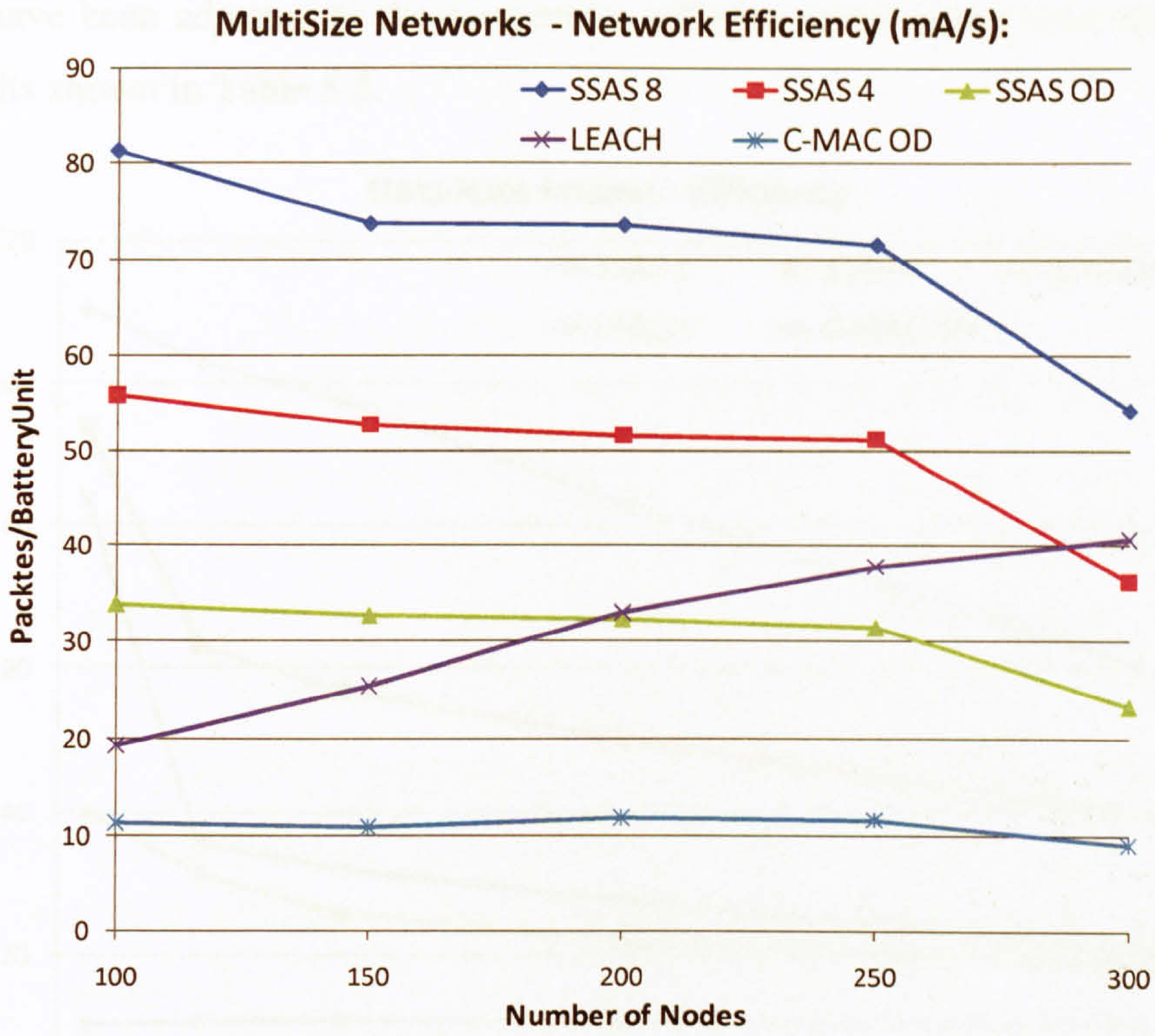


Figure 6.10 – Impact of network size (=density) in the Energy-Efficiency

6.3.5 Impact of Data Rate

To evaluate the impact of the data rate on the network performance, Figure 6.11 compares the energy-efficiency achieved with SSAS, LEACH and C-MAC under different packet inter-arrival times. In this case, random topologies of 150 nodes and 610m by 610m areas with one sink located at the centre are simulated. Duty-cycles are adjusted to achieve more than 90% data delivery and the values selected for the different packet inter-arrival times are shown in Table 6.3. The efficiency achievements illustrated in Figure 6.11 are directly related with the ability of the protocol to reduce the active time (duty-cycle) while keeping the level of data delivery required.

Although efficiency decreases in SSAS with smaller data rates (higher packet inter-arrival time) the network life for SSAS alternatives are always higher than LEACH or C-MAC. With packets generated every one second, with the exception of LEACH, SSAS-4 and SSAS-8, a state of congestion collapse limits the maximum data delivery rate reached, 78% for SSAS_OD and only 37% in C-MAC; the duty-cycles have been adjusted to the congestion collapse point as has been indicated in the results shown in Table 5.2.

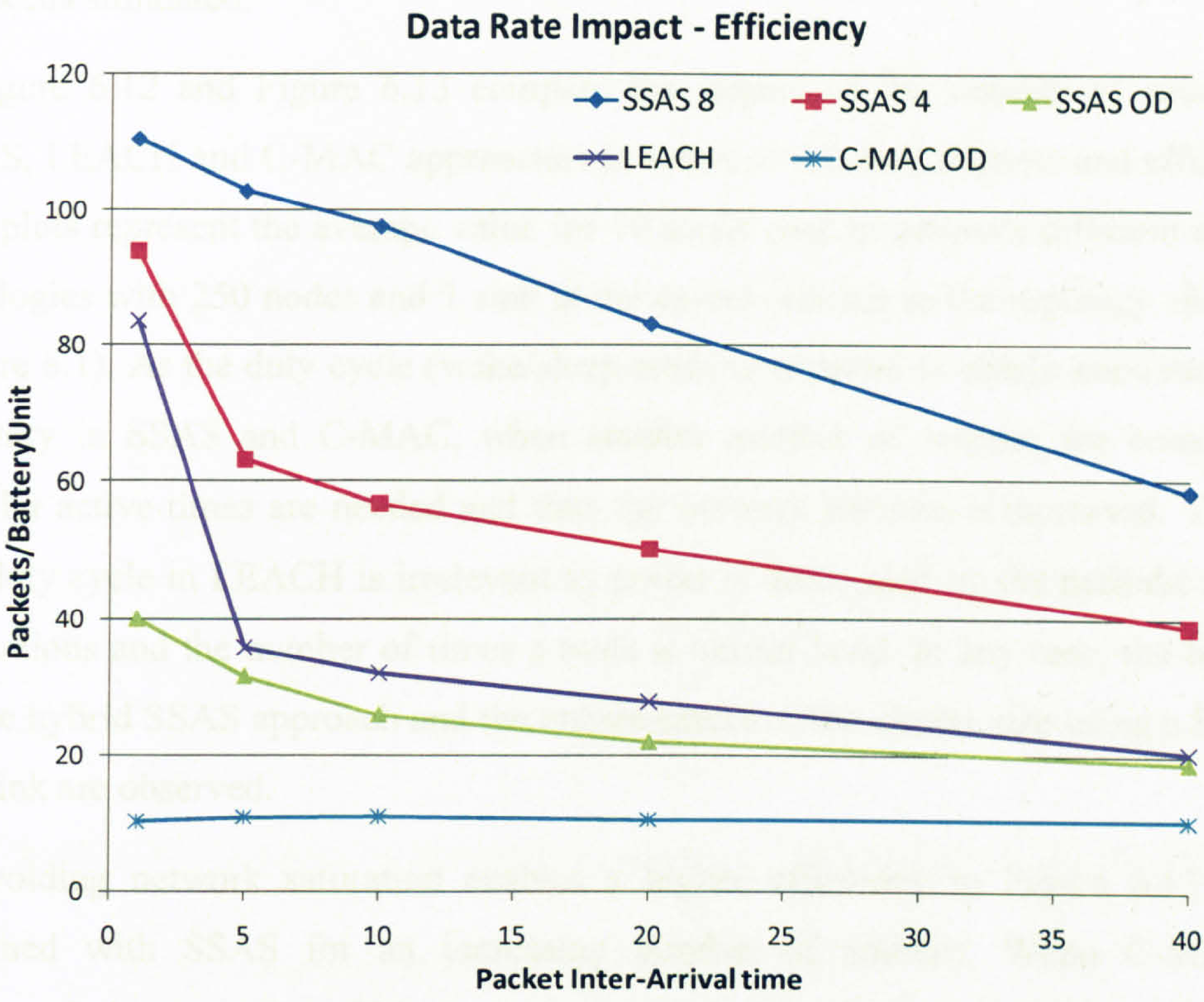


Figure 6.11 – Impact of data rate in the Energy-Efficiency (610x610m, *n*=150)

Table 6.3 – Inter-Arrival Packet Time and Duty-Cycle of Figure 6.11

Inter-Arrival	1s	5s	10s	20s	40s
SSAS_8	19.5	3	1.3	0.7	0.4
SSAS_4	24	6	2.5	1.5	0.8
SSAS OD	45	10	5.5	4	2
LEACH	30.2	9.8	4.3	2.2	1.1
C-MAC OD	60	25	15	8.5	5

6.3.6 Impact of Number of Sources

The network designer may have the possibility of using nodes acting only as relay nodes (and may have sensors to serve as backup). It should be noted that it is possible to add a few relay nodes in addition to the sensor nodes, which can be used to alleviate congestion and increase fault tolerance in the event of node failures. In such a scenario, designs with different combinations of MAC and antennas may be compared. The sources are represented by the nodes with IDs from 1 to the total value of sources (50, 100...) and the position of these sources will differ for each of the seeds simulated.

Figure 6.12 and Figure 6.13 compare the impact of the number of sources in SSAS, LEACH and C-MAC approaches in terms of network lifetime and efficiency. The plots represent the average value for 10 seeds used to generate different random topologies with 250 nodes and 1 sink at the centre (similar to the topology shown in Figure 6.1). As the duty cycle (wake/sleep ratio) is adjusted to obtain maximum data delivery in SSAS and C-MAC, when smaller number of sources are considered, smaller active times are needed and thus the network lifetime is increased. Varying the duty cycle in LEACH is irrelevant as power is dominated by the periodic cluster formations and the number of times a node is cluster head. In any case, the benefits of the hybrid SSAS approach and the enhancement of the cluster size using a SBA in the sink are observed.

Avoiding network saturation enables a higher efficiency in Figure 6.13 to be obtained with SSAS for an increasing number of sources. When C-MAC is employed, if more than 200 sources are used, a state of congestion collapse is reached as occurred in 6.3.3. Alternatively, increasing the data rate and/or network density can achieve in SSAS, with 250 sources, considerable more efficiency than that shown in Figure 6.13 before a congestion collapse state is reached.

Although not represented in the graphs, smaller delays, measured as the average in data acquisition time at the sink, are also achieved with SSAS, e.g. 5s in SSAS_8, 7s in SSAS_4, 10s in SSAS OD, 14s in LEACH and 17s in C-MAC if 250 sources transmit packets.

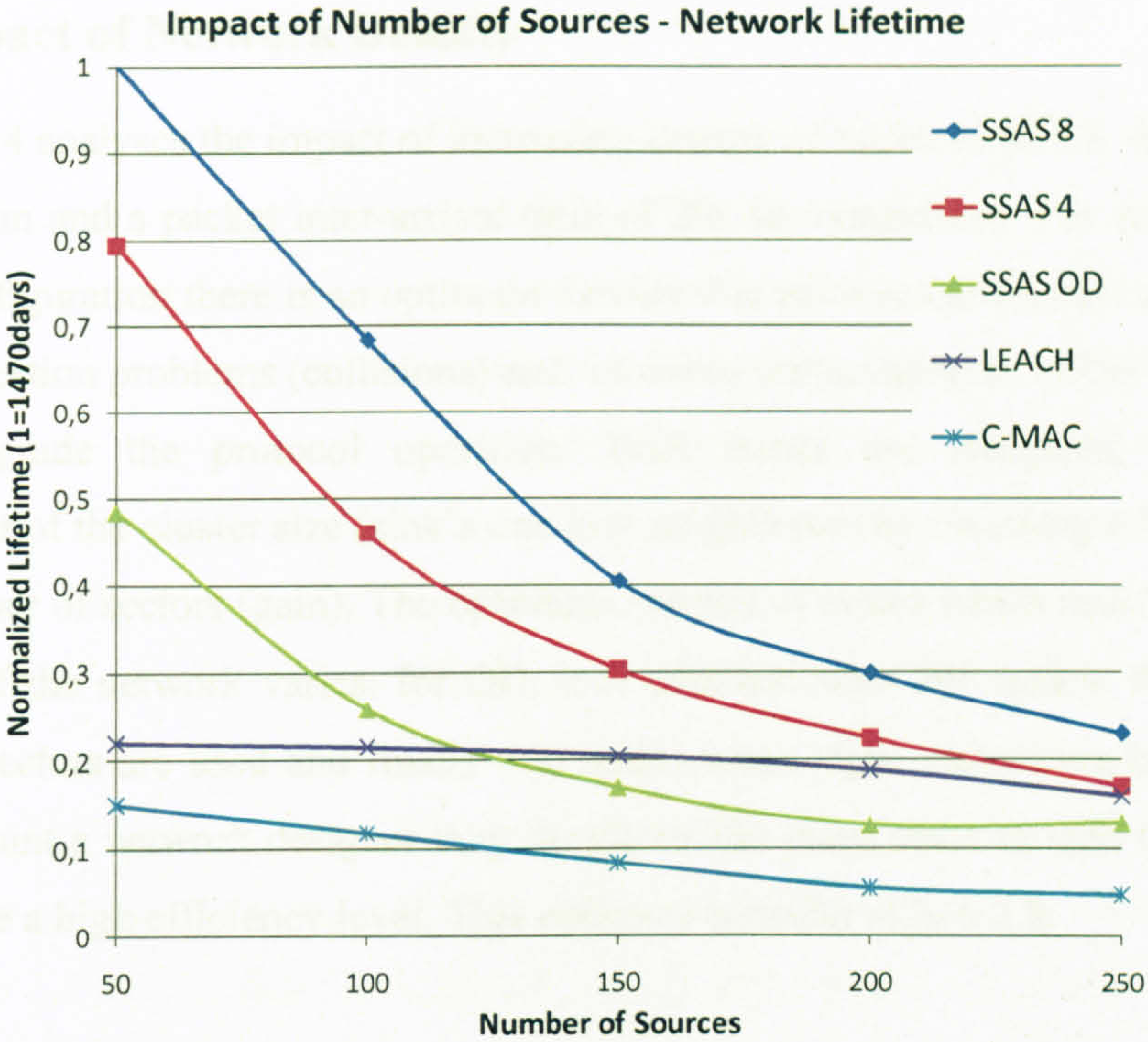


Figure 6.12 – Impact of number of sources in the Lifetime (750mx750m)

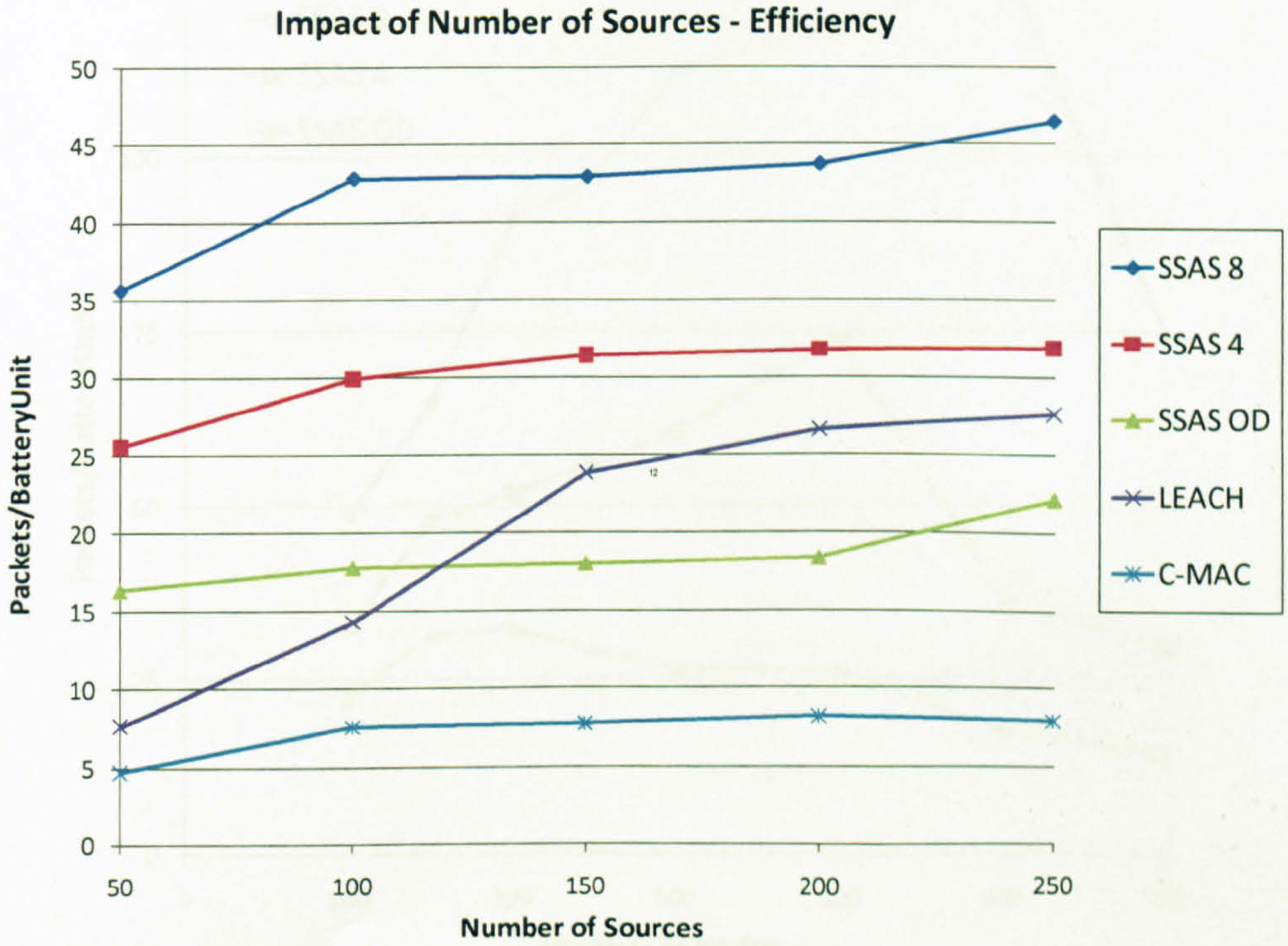


Figure 6.13 – Impact of number of sources in the Energy-Efficiency (750mx750m)

6.3.7 Impact of Network Density

Figure 6.14 analyses the impact of increasing density of nodes in SSAS. An area of 650m x 650m and a packet inter-arrival time of 20s are considered. For each SSAS antenna configuration there is an optimum density that achieves maximum efficiency before congestion problems (collisions) and, of minor transcendence, buffer overflow start to degrade the protocol operation. Both issues are mitigated with the enhancement of the cluster size (sink's one-hop neighbours) by choosing a SBA with higher number of sectors (gain). The optimum number of nodes which maximises the efficiency of the network varies: for OD, it is obtained with 200 nodes, 400 nodes when four sectors are used and finally 500 nodes when eight sectors are employed. After this point a network designer may decide to add more sinks to split the traffic and conserve a high efficiency level. This option is considered in 6.3.8.

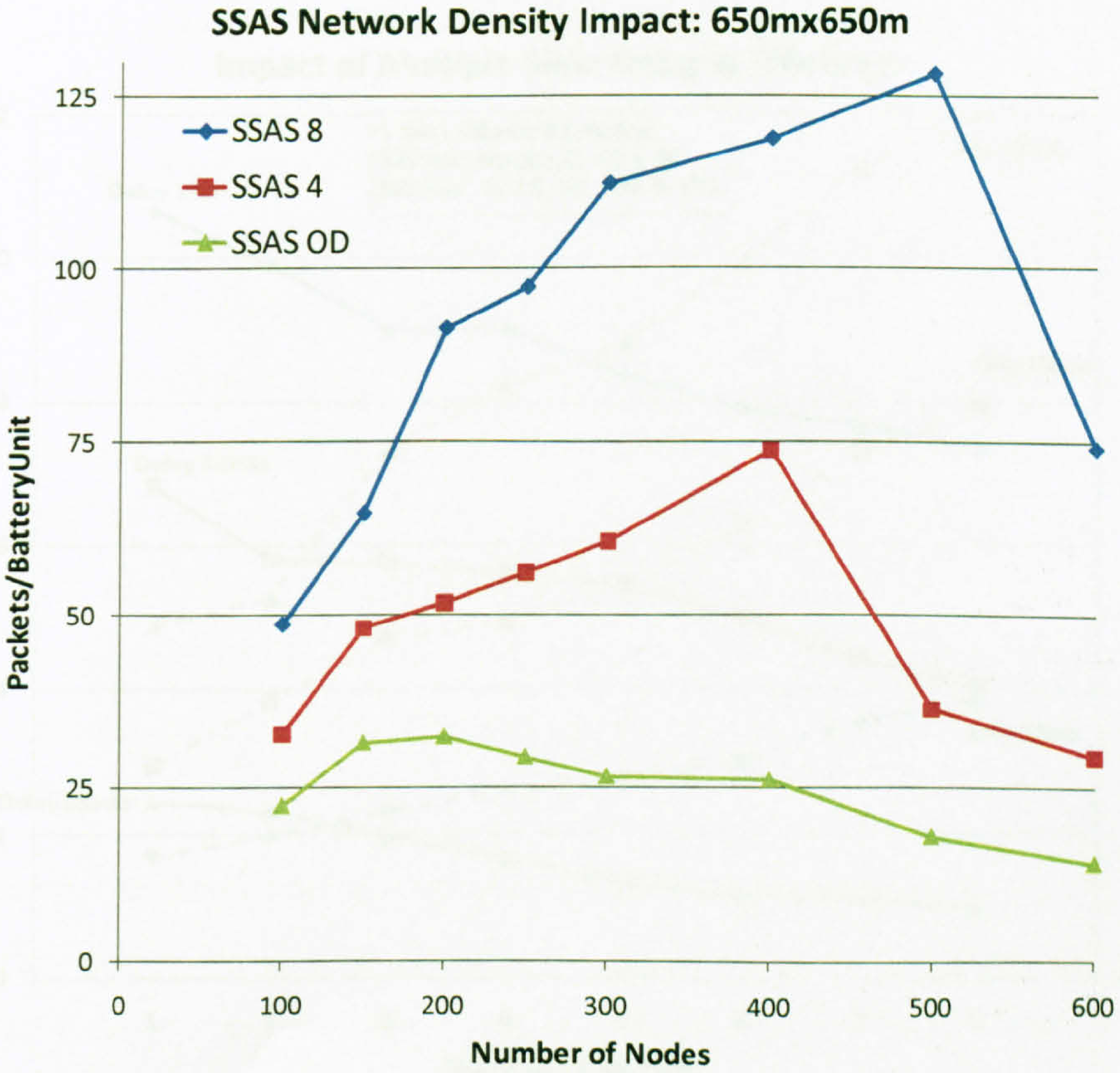


Figure 6.14 – SSAS. Impact of network density in the Energy-Efficiency

6.3.8 Impact of Multiple Sinks

The delay (left *y*-axis) and energy-efficiency (right *y*-axis) for multiple sinks configurations with different numbers of sinks' antenna sectors are shown in Figure 6.15 for the topology presented in Figure 6.1. The packet inter-arrival time is 20s and the frame duration 10s. Correlated with the network efficiency improvements, smaller delays are obtained when increasing the number of sinks and/or number of sectors at the sinks' SBA (antenna gain). An increase in both the number of Sinks and number of Sectors at the Sink (antenna gain), results in a reduction, on average, in the number of hops, an increase of number of nodes inside sinks' clusters and thus a high reduction of the congestion problems which occur if contention access is used. These results highlight again the benefits of the TDMA access in SSAS. With a SBA of eight sectors the efficiency, and approximately the lifetime, in SSAS can be multiplied by 3.2 and the delay decreased by eight if the number of sinks is increased from one to five.

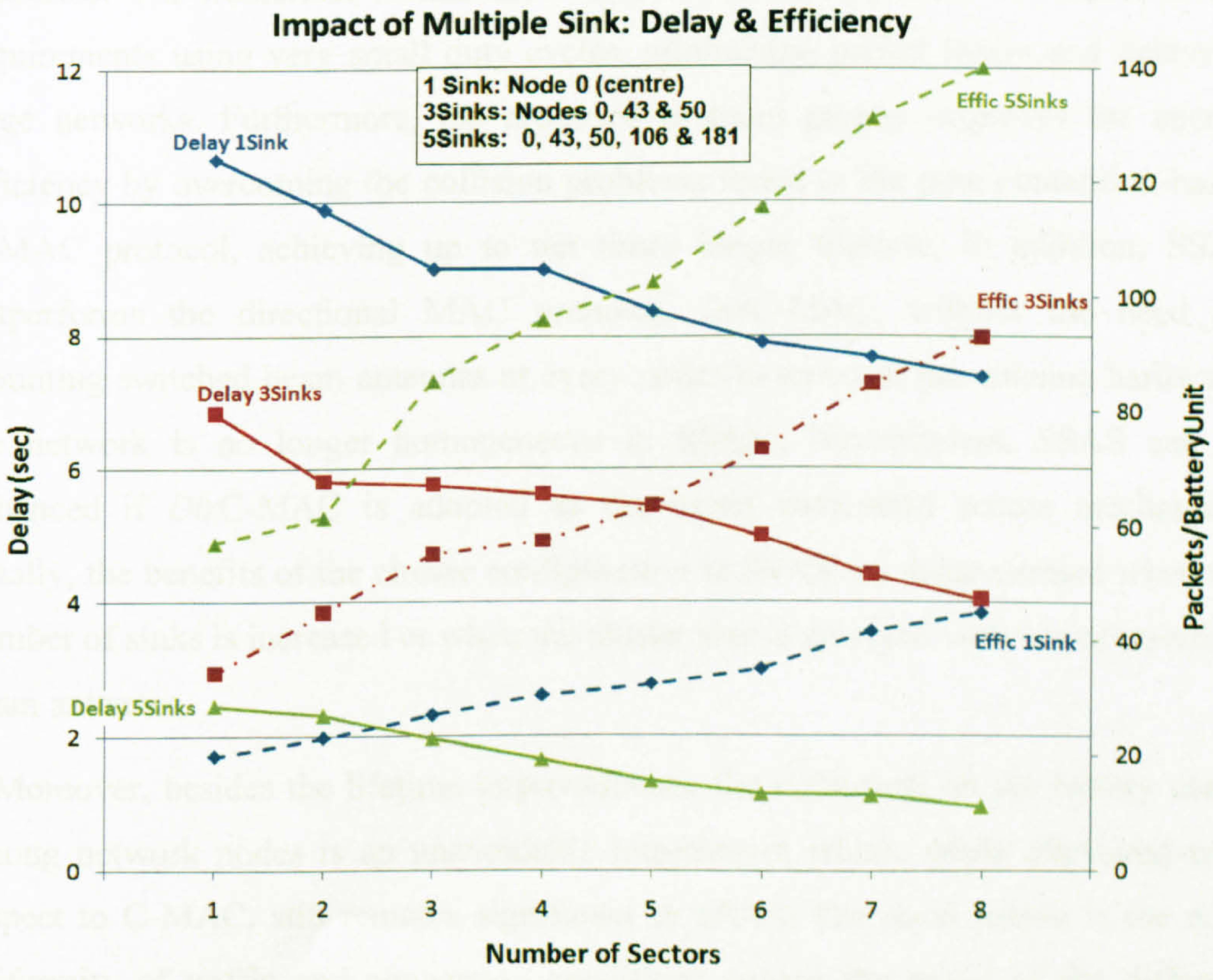


Figure 6.15 – SSAS. Impact of multiple sinks and number of sectors of each SBA sink in the network Delay and Energy-Efficiency

6.4 Summary

The Scheduling Sectorial Access at Sinks (SSAS) protocol is the main contribution to the cross-layer architecture XLCA; it offers a Routing/MAC/PHY cross-layer design with the implementation of a hybrid access control and the exploitation of directional antenna capabilities at the sinks.

SSAS efficiently merges the gap between contention and scheduled protocols, and thus minimises network saturation due to stringent duty-cycle requirement in Wireless Sensor Networks. It provides the benefits of the scheduled access at the sinks without losing the scalability and adaptability properties of the contention-based C-MAC. In addition, further adaptation techniques have been developed within SSAS to improve its performance under a range of changes: adaptive sleeping and slot assignment.

Extensive simulations have shown the superiority of SSAS in a wide range of scenarios. The numerical results show that SSAS accomplishes the data delivery requirements using very small duty cycles, minimising packet losses and delays in large networks. Furthermore, the proposed protocol greatly improves the energy efficiency by overcoming the collision problems found in the pure contention-based C-MAC protocol, achieving up to ten times longer lifetime. In addition, SSAS outperforms the directional MAC proposal, *Dir*C-MAC, without the need for mounting switched beam antennas at every node (in terms of the antenna hardware, the network is no longer homogeneous in SSAS). Nevertheless, SSAS can be enhanced if *Dir*C-MAC is adopted as the based contention access mechanism. Finally, the benefits of the cluster configuration in SSAS are demonstrated when the number of sinks is increased or when the cluster size is enlarged with use of switched beam antennas.

Moreover, besides the lifetime improvements, the unfairness on the battery usage among network nodes is an unavoidable impediment which, while alleviated with respect to C-MAC, still remains significant in SSAS. The main reason is the non-uniformity of traffic and congestion conditions among the nodes of the different routing trees towards the sinks. The proactive schemes proposed in the Chapter 7 are co-designed to mitigate these effects at the most vulnerable nodes.

It is concluded that, with the combination of scheduled sinks' access and enlargement of the one-hop relay area using switched beam antennas, SSAS can be implemented efficiently in large random deployments allowing more stringent applications with time-critical traffic and adapting to network dynamics.

Chapter 7

Proactive Solutions for Energy-Vulnerable Nodes

Inside the cross-layer architecture XLCA, the communications solutions *Dir*C-MAC and SSAS have accomplished the fundamental design challenge in energy-constrained WSN, that of increasing the operational network time. Especially the adoption of a hybrid MAC scheme and the use of sectorial clusters in SSAS have shown important lifetime improvements. However, with increasing node density and multi-hop communications, the non-uniformity of traffic intensity and congestion level among nodes leads to uneven battery consumption and thus the existence of failure-prone nodes. In particular, some nodes closer to the sink become more saturated from the heavier data forwarding task, and thus tend to deplete their batteries notably faster, terminating the network operation once they have failed as the sink becomes isolated. It is therefore essential to incorporate failure-tolerant schemes to postpone failures and/or to mitigate the impact after energy-vulnerable nodes fail. With a prompt detection and actuation, the lifetime of these critical nodes and thus the network operation can be significantly extended.

Using SSAS as the core communication protocol, three independent proactive schemes have been devised across the protocol stack:

- in the MAC layer, the hybrid TDMA-CSMA/CA mechanism is further extended from one hop to selective multiple hops featured with vulnerable nodes;

- in the routing layer, dynamic routing protocols allow the neighbours of vulnerable nodes to share the loads without provoking excessive routing overhead;
- in the application layer, mobile robots with directional antennae are employed to rescue failing nodes.

It can be noticed that the use of mobile robots is very application specific and constrained to the practicability and cost of current robot technology. However the mobile robot has been considered to emphasise the performance of the proactive hybrid MAC approach without the need of nodes replenishment.

The proactive solutions are initiated autonomously at the most vulnerable nodes with the premise that a detection mechanism is provided. A new physical-layer metric called *Battery Index* (*BI*)[3] is demonstrated as being effective in predicting energy-vulnerable nodes without global knowledge at the very early stage of the network's operation.

7.1 Vulnerability Detection

The proactive failure management schemes here proposed apply to the predictable energy-vulnerable nodes. The first challenge arises in how to detect these nodes. With the objective of providing local detection without network information exchange, which is needed for example if the *Residual Battery* [75] is used, several metrics at the Routing-MAC layer have been explored. Routing metrics such as the number of senders, packets forwarded per frame, the number of neighbours or, how many of these compete to access the same next-hop, help to categorise each node in terms of traffic activity and contending conditions that propitiate congestion problems. A more representative assessment of congestion is obtained with the MAC contention metrics such as collisions, overhearing packets, retransmissions, the contention metric $((RTS_{sent} - CTS_{received})/RTS_{sent})$, buffer occupancy, among others, which can be used to trace the congestion level at every node. Evaluation of these metrics helps to clarify the causes of vulnerability at certain nodes and has motivated the design of the dynamic routing and hybrid MAC proactive solutions.

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[3] Devised by Dr. Qi Wang [107] within the DIAS-MC project, to detect vulnerable nodes and used to trigger the proactive schemes designed within this thesis.

However, consideration of these metrics does not converge into a solid conclusion and none of these routing and MAC metrics has been found sufficient to identify the nodes that consume more energy.

Ultimately, the effect of high traffic and congestion problems is an increasing utilisation of the radio resources; in particular the power hungry states Rx and Tx (see energy consumption of the CC2420 in Figure 4.7). In real applications, the MAC can trace the amount of time spent in the different radio states during the active time to accumulatively estimate the *Residual Battery* ('the distance'). Alternatively, the *Battery Index* metric measures 'the speed' in which the radio uses the battery during the active time. Hence the use of this metric can avoid the need of comparison against other nodes if the threshold that identifies an excessive 'speed' is known in advance.

7.1.1 Battery Index

Intuitively, the underlying theory is that battery-vulnerable nodes consume more averaged energy over time; the Battery Index (BI) is defined as,

$$BI = K \cdot \frac{T_{Tx}(t) + T_{Rx}(t)}{T_{Sleep}(t) \cdot D_c} \tag{6}$$

Where: $T_{Tx}(t)$, $T_{Rx}(t)$ and $T_{Sleep}(t)$ are the accumulated times of the Transmit (Tx), Receive (Rx) and Sleep modes in period t, respectively; D_C the duty cycle (the ratio of active time to the total of sleep and active time in a frame); K a constant scaling factor.

Since very low duty-cycles are used in WSNs, the divisor part of (6) is representing the network active time, thus BI reflects which portion of the time is used in the costly radio states (Tx and Rx). Generally, the higher the value of BI, the faster a node fails. An advantage of this metric is that it explicitly takes into consideration the duty-cycle and thus adapts to its value, which is a fundamental characteristic in WSNs. Secondly, the value of the metric remains sufficiently stable after the network initialisation stage. Thirdly, the metric can thus be used to predict energy-vulnerable nodes at a very early stage, which is crucial for many proactive schemes. Finally, signalling and processing overhead can be significantly reduced in algorithms where collection and comparison of global battery state information is required.

7.2 Schemes to Circumvent Energy Vulnerability

To co-design cross-layer proactive schemes to circumvent the vulnerability from unfair battery use, analyses of the network conditions are needed. Since SSAS has largely reduced the impact of idle listening, vulnerable nodes are mainly determined by the congestion level together with traffic load, which are closely related in contention-based MAC. Ultimately, highest *BI*s in the network are found in nodes that have heavy traffic and are located in congested areas, especially in those that are close to the sink.

The lifetime of these vulnerable nodes may be prolonged through routing or MAC techniques. Intuitively, traffic balancing routing strategies applied at their senders may reduce traffic load at these nodes. Alternatively, adapting the MAC operation of both these vulnerable nodes and their senders may alleviate the congestion level. In either approach, tradeoffs and implications to the rest of the network need to be assessed to choose an optimal proactive scheme. For example, if distributing the traffic destined to a vulnerable node implies a load increase in another vulnerable node, the solution can actually deteriorate the network usability.

Another possibility is to replace manually, or by the use of a robot, the nodes that have failed, but without incurring changes in the network operation (MAC and Routing). The three proactive solutions, a hybrid MAC, a dynamic routing and a mobile robot, are add-ons to improve SSAS and have been implemented in the XLCA platform on top of SSAS. These schemes are explained in the next sections 7.2.(1-3) and will be evaluated and compared to the baseline reactive re-routing included in XLCA (Section 4.1.5.1).

7.2.1 Proactive Hybrid MAC: Pro-SSAS

Motivated by the improvements in SSAS with a scheduled access to sinks, *Pro-SSAS* is proposed here to apply the hybrid MAC concept in the most vulnerable nodes, which are most likely to be one or two hops away from the sink. Swapping to

TDMA access enables vulnerable nodes to remain sleeping during the contention active periods and also reduces congestion at their senders. The implementation of *Pro*-SSAS is illustrated in Figure 7.1(a) that shows a network portion with one- and two-hop vulnerable nodes.

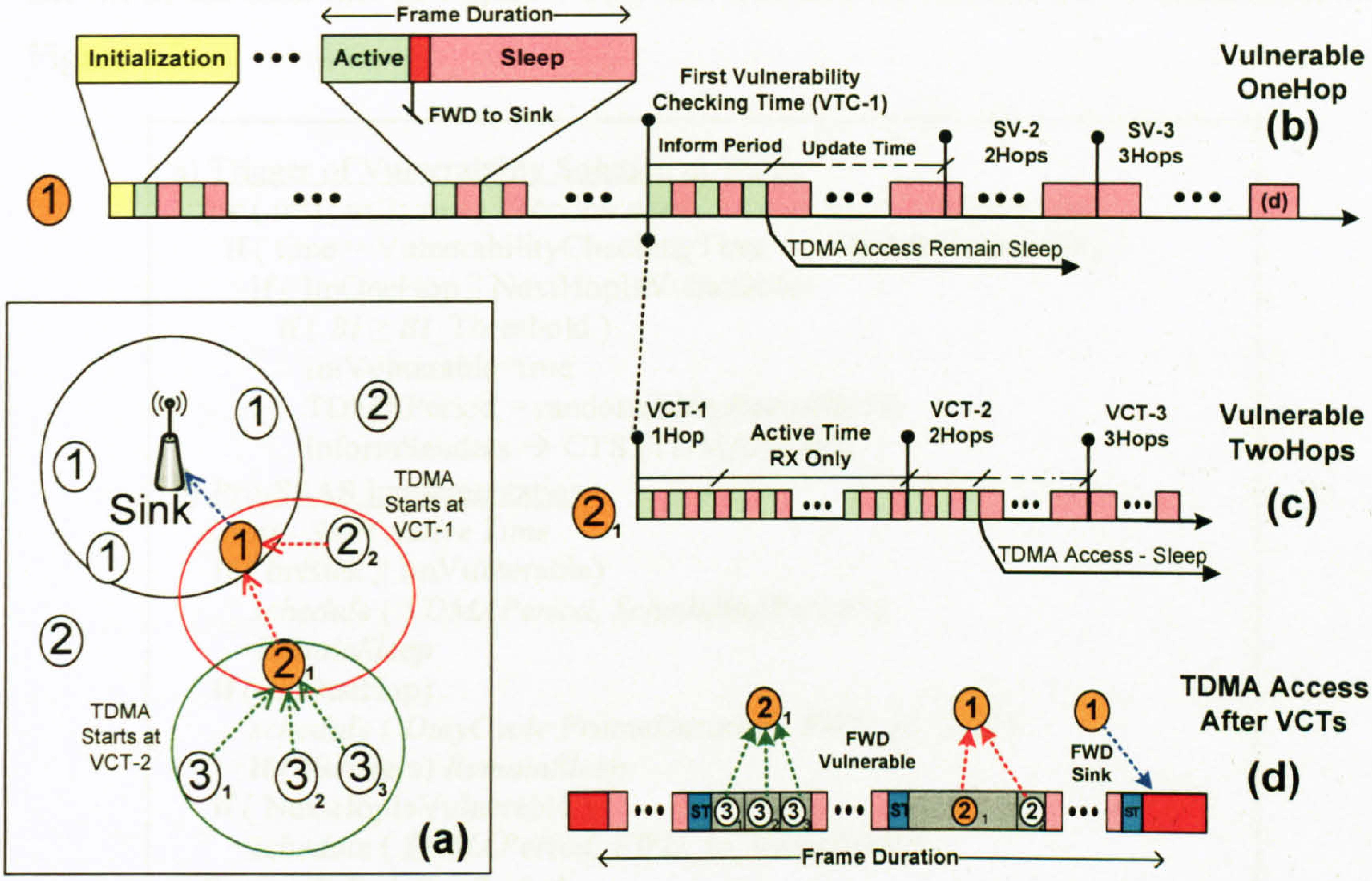

Figure 7.1 - Time diagram of Pro-SSAS: (a) Multi-hop scenario, (b) Timeline of one-hop, (c) Timeline of two-hops and, (d) Scheduling access timeline of vulnerable nodes.

The proactive scheme is performed autonomously, locally and hierarchically up to three hops from the sink in the current implementation although this approach can be further extended. When Pro-SSAS is triggered, the senders of the vulnerable-nodes only receive packets and that the contention level is reduced and the forwarding process from further hops is accelerated. In the scenarios evaluated in this chapter, with the buffer size (Table 4.1) and network sizes assumed, buffer overflow does not occur.

In *Pro*-SSAS, a two-hop node is not allowed to start the proactive scheme if its parent one-hop is not vulnerable itself. A two-hop vulnerable node cannot remain sleeping if it needs to contend during the active time to forward the packets to its non-vulnerable one-hop parent node. However, since the one-hop node experiences at least the same amount of traffic as its senders do and both have similar congested channel in the neighbourhood, the above scenario is unlikely to happen. Hence, the TDMA enhancement is started at different Vulnerability Checking Times (VCT) as shown in the time line of Figure 7.1(b) and described in the pseudo code included in Figure 7.2.

```
a) Trigger of Vulnerability Solution at VCTs
  for ( n=1; $n \leq 3$; n++) //Action made 3 times, up to 3-hops nodes
    if ( time = VulnerabilityCheckingTime + n·UpdateVulnerbility )
      if ( ImOneHop || NextHopIsVulnerable)
        if ( $BI \geq BI$_Threshold )
          ImVulnerable=true
          TDMAPeriod = random(SleepPeriod/0.1s)
          InformSenders → CTS (TDMAPeriod)
b) Pro-SSAS implementation
  Event - Start Active Time
   if ( ImSink || ImVulnerable)
     schedule ( TDMAPeriod, SchedulingPeriod )
     RemainSleep
   if ( ImOneHop)
     schedule ( DutyCycle·FrameDuration, FWD_to_Sink )
     if ( !Senders) RemainSleep
   if ( NextHopIsVulnerable )
     schedule ( TDMAPeriod, FWD_to_Vulnerable )
  Event – SchedulingPeriod
    if ( ImSink || ImVulnerable)
     sendScheduleTable(ST)
     schedule ( totalPackets, sleep ) //Sleep after Rx during assigned slots
  Event - FWD_to_Sink  & FWD_to_Vulnerable
   if ( ImOneHop || NextHopIsVulnerable )
     ReceiveScheduleTable(ST)
     ST→ GetMySlot & Synchronize
     schedule ( MySlot, SentPackets )
```

Figure 7.2 - The pseudo-code of *Pro*-SSAS

An *inform period* of several frames, to ensure fully notification, is used to report the senders with the scheduling access time, which is randomly chosen from one of the 0.1s (74 packets) slots inside the long sleep period. To avoid extra delays, one-hop nodes choose slots in the second half of the sleep period whilst further hops do so in the first half of the sleep period. Thus, vulnerable nodes remain sleeping as shown in Figure 7.1(b) and (c). Adequate vulnerability update time is allowed between VCTs. The update time between VTCs enables the traffic and congestion conditions, and thus the *BI*, to stabilise after the adoption of TDMA access. Update periods of 10 frames have been found sufficient in simulations, yielding better results if shorter update periods are used. Similar to the cluster SSAS operation explained in Section 6.2, the slot assignation to the senders is informed in the scheduling table (ST), which is sent every frame before the data forwarding to keep synchronisation with senders. Initially, the slots sizes are given to each sender regarding the tracked average packets received from these. Figure 7.1 (d) shows the frame timeline events of vulnerable nodes 1 and 2_1 after VCT-1 and VCT-2.

Network simulations have confirmed that *Pro*-SSAS significantly changes the congestion conditions of the vulnerable nodes as well as the whole neighbourhood and even further hops. Eventually the scheduling access can be extended to the whole network ending in a complete TDMA graph. However, as discussed in Section 3.2.3.2, this scenario is neither attractive, nor realistic, in the likely scalable and dynamic sensor networks applications. Therefore, as a trade-off, the extension of the proactive TDMA in *Pro*-SSAS is applied only in the most vulnerable nodes (around 10% of the total number of nodes is preferred). Nevertheless, the results presented in Section 7.3 will show the superiority of the hybrid MAC against reactive and proactive routing schemes.

7.2.2 Proactive Load-Sharing Dynamic Routing

To accelerate the detection of vulnerable nodes and the subsequent rerouting in the Reactive Rerouting scheme (Section 4.1.5.1), an immediate improvement has also been studied: a dying node (whose *Residual Battery* is lower than a threshold) notifies its neighbours of its battery shortage and requests them to start re-routing. Nevertheless, it is usually too late to benefit from a proactive scheme and the improvements are marginal.

Therefore, it is proposed to apply more proactive *BI*-based dynamic routing significantly in advance of the vulnerable nodes approaching extinction. The basic idea is that the routing protocol has the traffic loads originally destined to a vulnerable node shared by its neighbour(s). At the same three vulnerability checking times shown in Figure 7.1, every node checks its own *BI*; if its *BI* is greater than the predefined threshold, the node considers itself as a vulnerable node and then triggers the vulnerability solution. A vulnerable node notifies its neighbouring senders of its vulnerability through local signalling. Such information can be piggybacked in RTS/CTS messages. Figure 7.3 summaries a pilot algorithm: If the next-hop node is a vulnerable node identified by the *BI*, for each RTS-CTS-DATA-ACK round, the routing protocol at the sender selects the next "best" one in the routing table with a probability *p*. This scheme is referred to as SSAS+dRouting1.

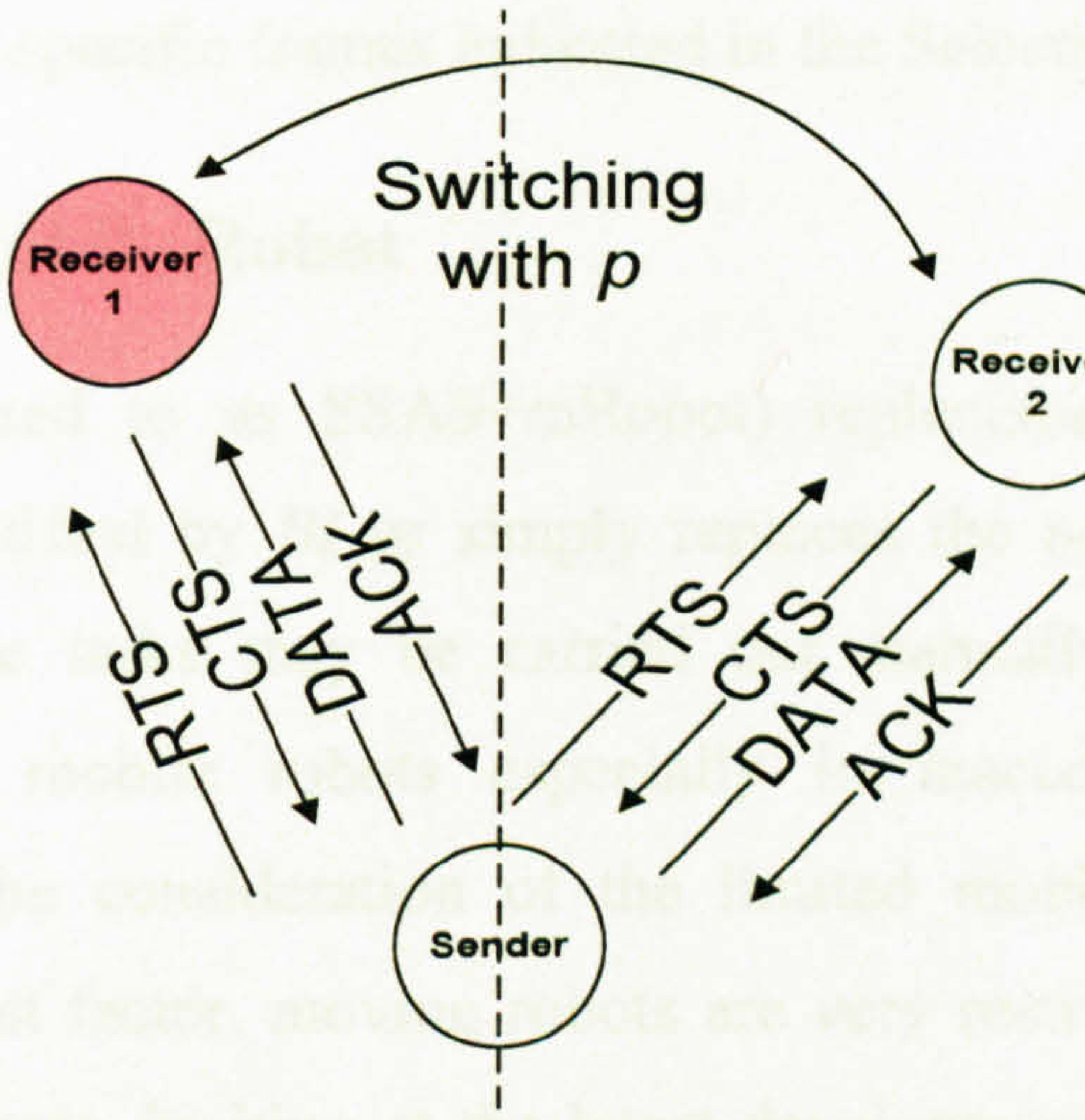

Figure 7.3 - Proactive dynamic routing

In a more advanced version entitled as SSAS+dRouting2, a vulnerable node sends the vulnerability *Notification* to all its neighbours and the number of frames it will be asleep. Compared with the pilot version, now the vulnerable nodes can go to sleep in the otherwise active time to save further energy. After receiving the Notification, each sender of the vulnerable node sends a Selection message, selecting the next-hop neighbour that will be used as next-hop when the vulnerable node is sleeping. The new next-hops of these senders will be aware of these new senders and in which frames they will need to replace the vulnerable node. If the new next-hop is a one-hop node that is currently sleeping during the active time because they do not have any sender, this node now will wake up to receive packets from the new senders only in the assigned frames, however it can remain sleeping when the vulnerable node is working.

It should be noted that the adaptive sleeping mechanism in SSAS (explained in 6.2.2) keeps asleep the one-hop nodes that do not belong to any routing chain towards the sink, i.e. those that have no senders. This fact limits the ability of two-hop senders of a one-hop vulnerable node to select an alternative one-hop node, which, if they remain asleep will not be aware of the need for rerouting. Due that every node has been noticed in the initialisation with the VCTs, the solution proposed forces every node, firstly, to remain awake the active times at the VCTs, and secondly, in the case that the node has been selected as next-hop, to remain awake no less than the specific frames indicated in the Selection message.

7.2.3 Proactive Mobile Robot

This scheme (referred to as SSAS+mRobot) replenishes the batteries of the vulnerable nodes identified by *BI* or simply replaces the nodes themselves before they actually die. The tasks may be carried out manually, although it is more desirable to employ mobile robots especially in inaccessible or inhospitable environments. With the consideration of the limited mobility of current robotic technology and the cost factor, moving robots are very restricted in the majority of WSN scenarios. However, looking at the latest developments in the area [108] the use of robots within sensor networks may be feasible in future.

In this scheme, the mobile robot is initially driven to start its journey after the predefined vulnerability checking time (VCT), when each node checks its *BI* independently as described. A vulnerable node then starts broadcasting Battery Alert messages periodically, until acknowledged by the robot. Alternatively, the robot announces its presence by broadcasting while moving around. A non-vulnerable node only broadcasts alerts when its *residual battery* runs below a predefined threshold. It is noted that the robot moves at a low speed and thus it can take a considerable time to cover its service area once. Moreover, its capacity to carry spare sensor nodes or to recharge sensors is limited. By allowing early alerts, vulnerable nodes are able to receive prioritised service from the robot. When the robot approaches a vulnerable node, it disposes a backup node beside the vulnerable one and then continues its patrol. The backup node initially uses an ultra-low duty cycle to maintain the contact with the vulnerable node at the cost of extremely low battery consumption. Both nodes schedule a slot every few frames (e.g. three) where the vulnerable node sends an *alive* packet. When this node dies, thus the backup node stops receiving the alive packet, it takes over and changes to the duty cycle in use in the network. For non-vulnerable nodes, they are simply recharged or replaced.

In addition, two design challenges have been addressed. Firstly, an effective and efficient route has to be discovered for the mobile robot. Given the fact that the most vulnerable nodes are typically located one hop or two hops away from the sink and these have more significant impact on network coverage, it is not efficient for an energy-constrained robot to randomly cover the whole sensor network area to pass by all the vulnerable nodes. Actually, in the current implementation the robot only moves in the one- and two-hop areas, following a square or circular trajectory by default repetitively. Such a route is simple yet realistic for mobile robot's movement although an optimised itinerary can be researched in future work.

Secondly, a realistic mechanism has to be in place for the mobile robot to identify the location of the vulnerable nodes when passing by them. The mobile robot detects a vulnerable node on receiving a Battery Alert, and then approaches the node to perform rescue. The mobile robot identifies the exact location of the node through switched beam directional antennae, as illustrated in Figure 7.4.

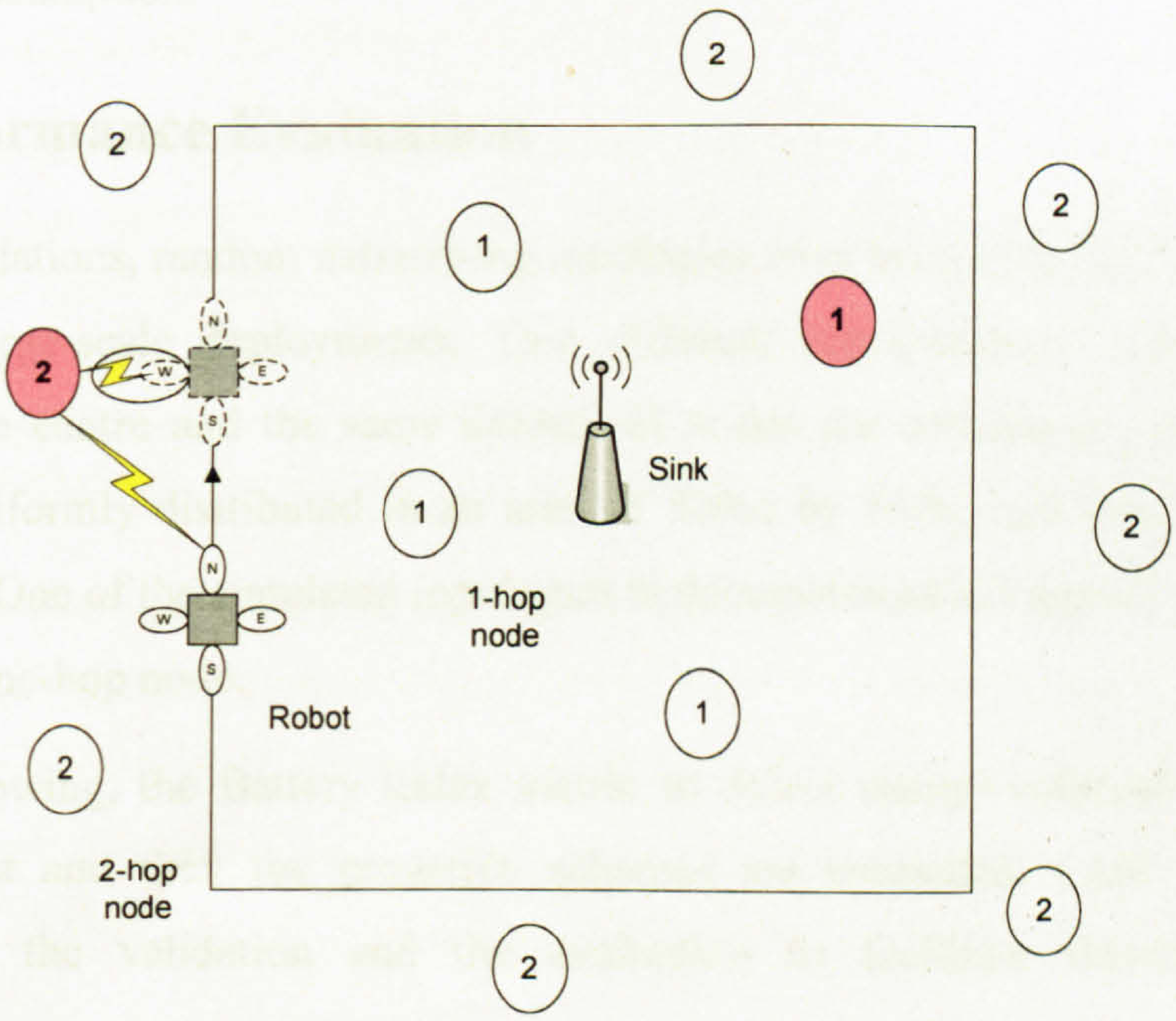

Figure 7.4 - Location detection of vulnerable nodes by a mobile robot.

Existing work such as [109] typically employs reactive schemes to fix failed nodes when damages have already been done due to the node failure. Moreover, in the literature unrealistic grid-based network topologies (e.g., [109]), pre-knowledge of nodes' locations (e.g., [110]) or location detection through the Global Positioning System (GPS) (or complex positioning algorithms such as [111]) are commonly assumed to enable the mobile robot's journey planning.

Although the proposed proactive dynamic routing and the node rescue schemes are independent from each other, they can be applied jointly. Particularly, in sparse WSNs, many nodes especially the vulnerable ones are very likely to have no neighbours to share the loads. Therefore, it would be desirable to add load-sharing nodes to prolong the lifetime of the vulnerable nodes. Such topology enhancements should be performed far before the vulnerable nodes actually die. Among other possible mechanisms, mobile robots again can be employed to dispose a load-sharing node beside a vulnerable peer and then the load sharing can be conducted through the described dynamic routing. It is noticed that if only *Residual Battery* is used without *BI*, the robot would have to collect and compare all the battery values to find out the likely vulnerable ones; and all the nodes would have to report their battery states. Such operations will provoke substantial signalling and processing overheads as well as battery consumption.

7.3 Performance Evaluation

In the simulations, random networking topologies have been generated to represent real-world large-scale deployments. Two different configurations with one sink located in the centre and the same density of nodes are considered: 100 and 150 nodes are uniformly distributed in an area of 500m by 500m and 610m by 610m, respectively. One of the simulated topologies is demonstrated in Figure 7.5, where 🟦 stands for a one-hop node.

In the following, the Battery Index metric to detect energy-vulnerable nodes is validated first and then the proactive schemes are evaluated. Case studies are presented in the validation and the evaluation to facilitate illustrations and explanations, followed by averaged performance results obtained based on numerous simulations.

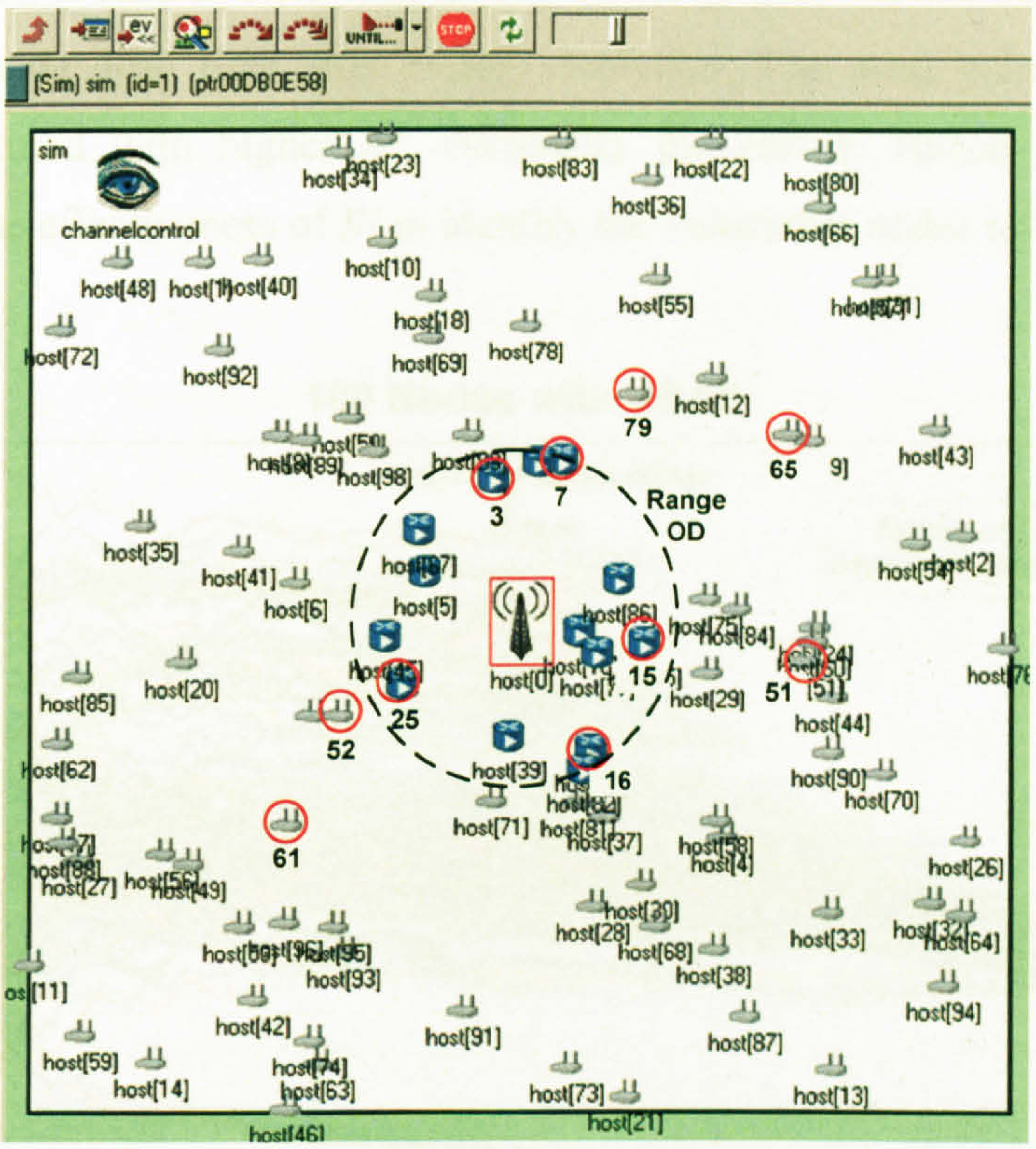

Figure 7.5 - Simulation snapshot of a typical WSN

7.3.1 Validation of the Battery Index

The effectiveness of the BI metric has been validated under various conditions. The experiments have been performed using the protocol SSAS with proactive schemes; In addition, the suitability of the Battery Index to identify vulnerable nodes has been also confirmed in C-MAC. The case study described in Section 7.3.1.1 illustrates the effectiveness of the Battery Index in detecting vulnerable nodes and how a proactive scheme applied at these nodes impacts the behaviour of this metric.

7.3.1.1 Case study: battery index behaviour in SSAS and in Pro-SSAS

Figure 7.6 (a) illustrates the evolution of the nodes' *BI* and correlated lifetime in the networking scenario shown in Figure 7.5 using SSAS without any proactive scheme. Figure 7.6 (b) represents the impact of a proactive scheme, in this case *Pro-*SSAS, on the *BI* of the top 10 vulnerable nodes marked in Figure 7.5.

To accelerate the deaths of the nodes for demonstration purpose, the initial battery capacity of each node (except the sink) is set to be 150 mA·s in Figure 7.6 instead of the 300mA·s that is used in following results. In the graphs, the end of the *BI* curves represent the node dead time after battery depletion. The most vulnerable nodes, which are featured with higher *BI*, eventually die earlier. Hence Figure 7.6(a) demonstrates the effectiveness of *BI* to identify the vulnerable nodes in Figure 7.5.

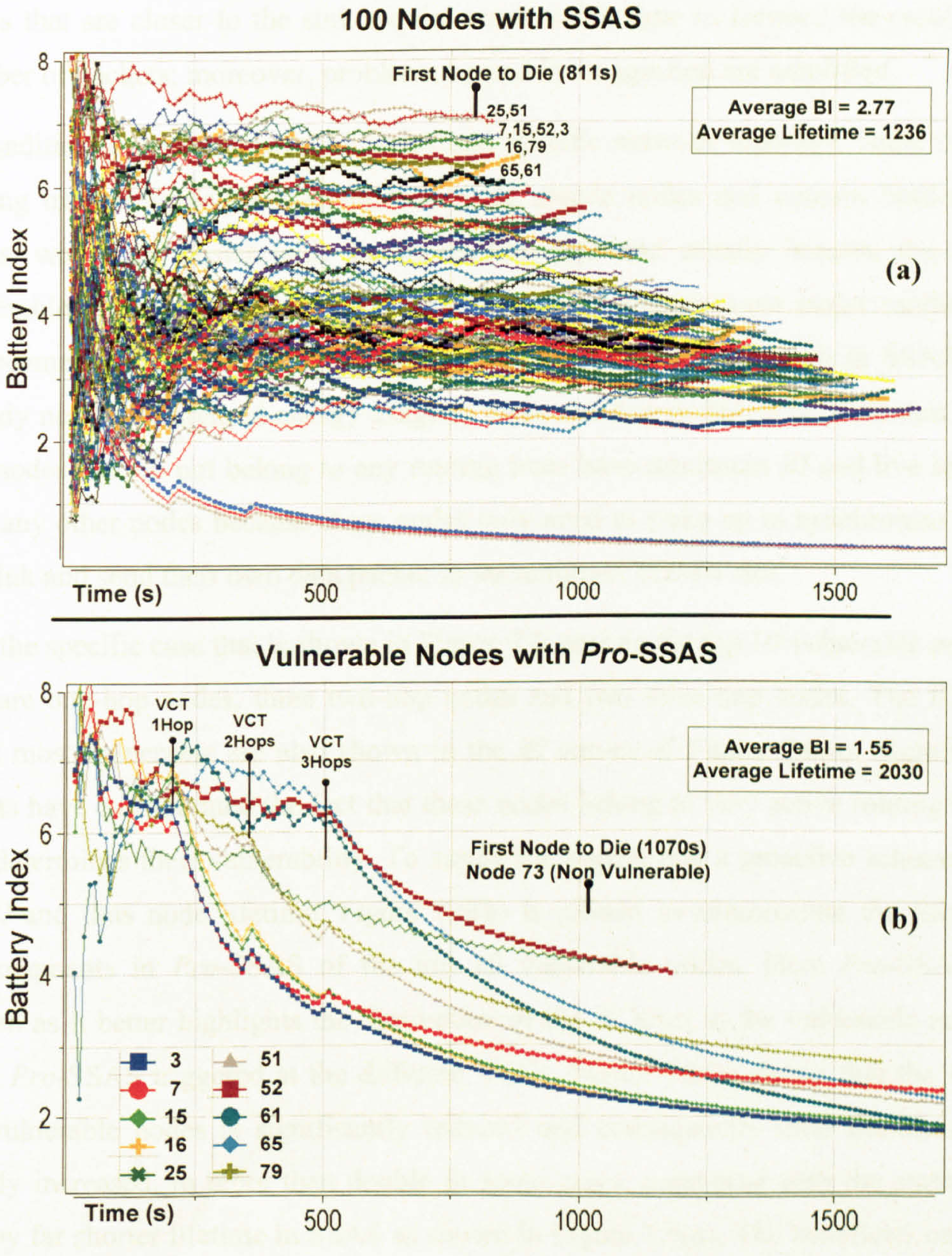

Figure 7.6 – BI variation: (a) SSAS and (b) Pro-SSAS for network in Figure 7.5

To understand the significant variation in the value of this metric among nodes in the network, it is important to consider the natural traffic conditions in multi-hop nodes-to-sink applications and recall the intrinsic operation of the adaptive SSAS protocol. With the *Adaptive Sleeping* mechanism, duty-cycles in SSAS are adapted locally to the specific needs of every node. For example, nodes that are located in the edges of the network only need to send their data packets towards the next hop and then they can go to sleep; as a result, these nodes have very low *BI*. In contrast, nodes that are closer to the sink require more active time to forward the escalating number of packets; moreover, problems caused by congestion are amplified.

Conditioned by the density of nodes and specific network topology, some of the routing trees towards the sink include more source nodes and contain bottleneck nodes, which are busier with the forwarding task and usually become the most vulnerable. Naturally one-hop nodes that belong to these trees are major candidates to become vulnerable nodes. Fortunately, the hybrid MAC approach in SSAS has already notably decreased energy usage at these one-hop nodes. It is noted that one-hop nodes that do not belong to any routing trees have minimum *BI* and live longer than any other nodes because these nodes only need to wake up to synchronise with the sink and send their own data packet in the assigned TDMA slot.

In the specific case that is shown in Figure 7.5, among the top 10 vulnerable nodes, five are one-hop nodes, three two-hop nodes and two three-hop nodes. The IDs of these most vulnerable are also shown in the *BI* curves of Figure 7.6(a). Simulation results have corroborated the fact that these nodes belong to very active routing trees that determines their vulnerability. To assess the impact that a proactive scheme has on *BI* and thus node lifetime, Figure 7.6(b) is plotted to demonstrate the lifetime improvements in *Pro*-SSAS of the top 10 vulnerable nodes. Here *Pro*-SSAS is chosen as it better highlights the diminution of the *BI* level in the vulnerable nodes. With *Pro*-SSAS triggered at the different VCTs, Figure 7.6(b) shows that the *BI* at the vulnerable nodes is significantly reduced and consequently their lifetimes are largely increased, to more than double in some cases, compared with the stable *BI* and by far shorter lifetime in SSAS as shown in Figure 7.6(a). The beneficial impact of the *Pro*-SSAS scheduling transmissions is also appreciated at the nodes transmitting to vulnerable nodes and the lessening of congestion is spread throughout the whole network. Comparing the results in Figure 7.6(a) and 7.6(b), the average *BI* of the entire network in *Pro*-SSAS is reduced by 44% whilst the average node lifetime is increased by 170% compared with the SSAS case. As shown in Figure 7.6(b), *Pro*-SSAS managed to circumvent vulnerability in every vulnerable node and the non-vulnerable three-hop node 73 is the first one that fails.

7.3.1.2 Results of repeated experiments on battery index

The effectiveness of the Battery Index has been further validated under various topologies and traffic conditions. Numerous different scenarios have been investigated with extensive simulations to record, classify and sort (highest to lowest) the *BI* of 100 or 150 nodes in different setting combinations. The application traffic type is periodic or bursty. Burst arrivals obey a Poisson distribution, and the number of packets in a burst is uniformly distributed from one to five. The packet or mean burst of packets inter-arrival time is 10 s, 20 s, or 30 s. Duty cycles are 1%~5%. 10 different randomly generated network topologies were tested. The scaling factor *K* is set to be 10 in all scenarios. The BI curves and correlated lifetime of the whole network for the different scenarios are comparable to the ones that have been illustrated in the example of Figure 7.6(a).

Based on numerous simulations, the following observations can be obtained.

- BI is an adequately stable and effective metric independent of the concerned traffic types, packet or burst inter-arrival time, network topologies and duty cycles.
- Generally, the higher the BI value of a node, the shorter the lifetime of that node (see Figure 7.6(a)). Typically, the BI values of the majority nodes range from one to five.
- BI = 6 seems a good threshold (when SSAS protocol is in use) to identify up to 10 vulnerable nodes on most of the occasions and thus this was used in the proposed proactive schemes.
- BI is usable when the network has just operated for as short as 100 s. The recommended time instance to sample BI is larger than 200 s since by then

the BI values are more stable. 210 s was chosen as the first vulnerability checking time VCT instance in the proposed SSAS-based proactive schemes.

A subset of one-hop and two-hop nodes in each simulation is most vulnerable. These nodes are more saturated with the forwarding task towards the sink but with reduced chances of competing for access to the channel. The probability that a node which dies first (top 1%) is either a one-hop or a two-hop node is over 90%. Given a topology, vulnerable nodes (or the order in which they die) can vary when the traffic type, packet or burst inter-arrival time or the duty cycle changes; however, *BI* can consistently capture them.

7.3.2 Comparison of Proactive Schemes

Through further simulations, the following five systems have been evaluated and compared:

1. C-MAC (base MAC in XLCA),
2. SSAS with reactive routing (simply SSAS),
3. SSAS with proactive hybrid MAC (*Pro*-SSAS),
4. SSAS with proactive dynamic routing (SSAS+dRouting1 and SSAS+dRouting2) and,
5. SSAS with proactive mobile robot rescue (SSAS+mRobot).

Periodic traffic is generated towards the sink, the packet inter-arrival time is 20 s and the frame duration 10 s. The duty cycle in all the SSAS systems is 1% whilst 5% has to be used in C-MAC to match the data delivery performance with that in SSAS (>90% as application requirements).

In the proactive dynamic routing, the routing scheme of a vulnerable node's sender selects the vulnerable node with $p = 0.7$. In the proactive node rescue, the mobile robot is set to be capable of rescuing up to 30 nodes and to move at the speed of 1 m/s in a square trajectory with sides 80m equidistant from the sink (similar to Figure 7.4). The initial battery capacity in all scenarios is set to 300 mA·s to speed up the simulations. In reality the typical value is 3000 mA·h, and thus every second actually represents 10 hour in the following numerical results (the corresponding days are noted in the parentheses). A number of performance criteria are considered.

- The first criterion is the lifetime of the first node to die (the most vulnerable node).
- The second criterion, network resilience, is defined as the period from the moment when the first node dies to the moment when the packet delivery ratio consistently drops below 50%.
- Thirdly, the overall network usability is defined as the elapsed time between the time instance when the network operation is started and the time instance when the packet delivery ratio consistently drops below 50% (when the network is considered unusable).

7.3.2.1 Case study: comparison of proactive schemes

Simulations have been conducted in various randomly generated network topologies and significant improvements in nodes' lifetime and network usability (in terms of the packet delivery ratio perceived at the sink) have been repeatedly observed. Figure 7.7 demonstrates a case study of the instantaneous data delivery ratio at the sink in the selected systems using C-MAC, SSAS and its enhanced variants when nodes run out of battery one by one in the network in Figure 7.5.

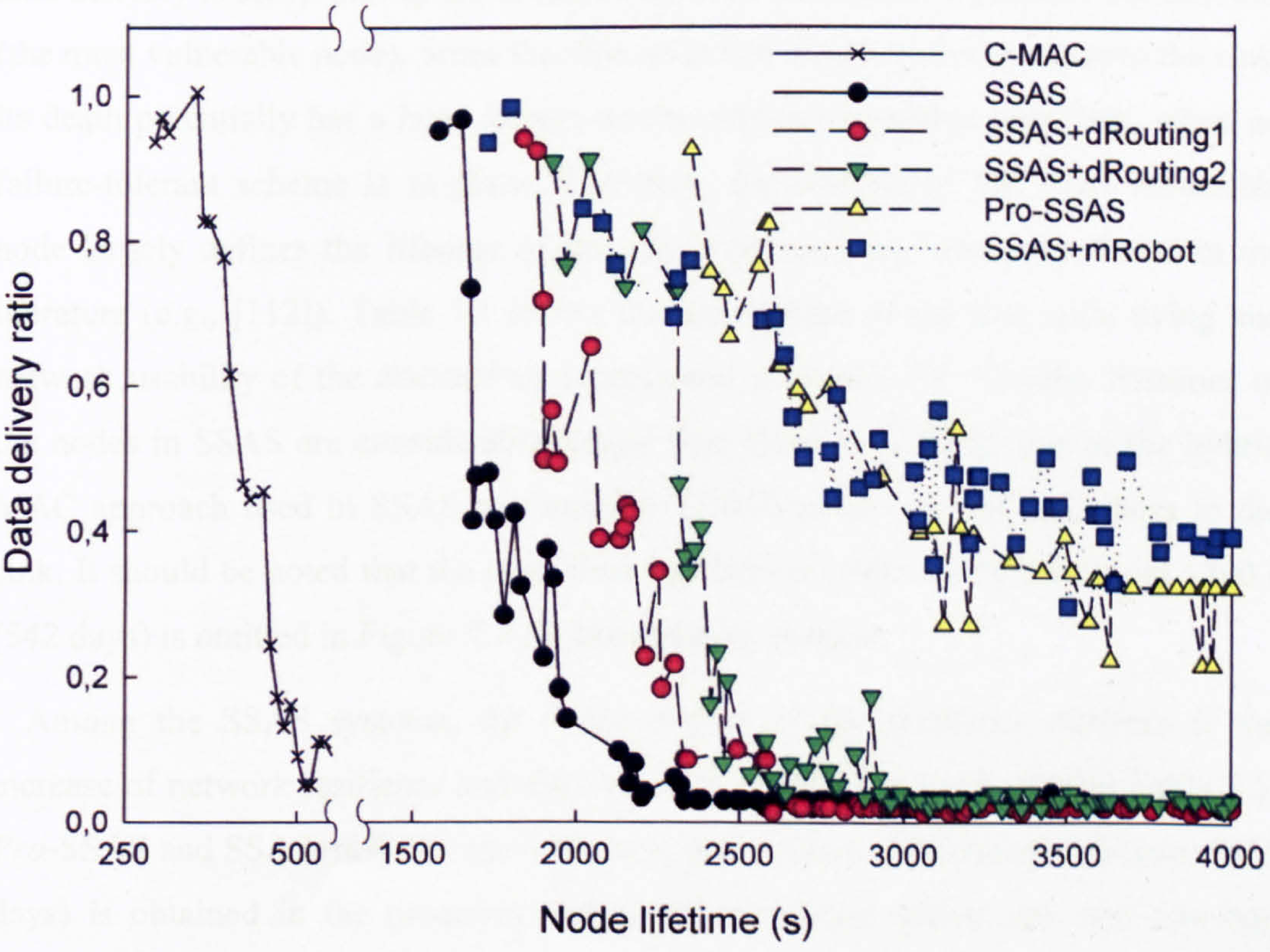

Figure 7.7 - Instantaneous data delivery ratio at the sink vs. node lifetime

As shown in Figure 7.7, with the gradual deaths of the nodes, the data delivery ratio in each system decreases despite the fluctuations due to the nature of a WSN (contention access and very small duty-cycles). In certain circumstances a slightly increase of data delivery at the sink is experienced after the death of a non-vulnerable node. Due to the reactive re-routing (explained in Section 4.1.5.1) the alternative routes selected to circumvent a node failure can provide higher data delivery compare to the initial shortest-path and minimum-distance routes (which are not necessarily optimal). Moreover, after a node has died, if it is not a one-hop node in SSAS, the contention level in the node's neighbourhood is reduced and the channel accessibility at its neighbours can be increased. In addition, because the data packets are not generated at the same instant in every node, the amount of data packets buffered previous each active time is irregular. This issue also justifies changes on the data delivery at the sink because the values represented in Figure 7.7 are the averaged data deliveries between death node times at the sink after each active time.

In the solutions without Proactive schemes (C-MAC and SSAS) the decrease of data delivery is sharp during the deaths of the first few nodes, especially the first one (the most vulnerable node). Since the first node that dies is typically close to the sink, its death potentially has a huge impact on the network operation especially when no failure-tolerant scheme is in place. Therefore, the lifetime of the most vulnerable node largely defines the lifetime of the whole network as commonly found in the literature (e.g., [112]). Table 7.1 shows the time values of the first node dying and network usability of the alternatives represented in Figure 7.7. Clearly, lifetimes of the nodes in SSAS are considerably longer than those in C-MAC due to the hybrid MAC approach used in SSAS that enables TDMA access of one-hop nodes to the sink. It should be noted that the huge time gap between 600 s (250 days) and 1300 s (542 days) is omitted in Figure 7.7 for presentation purpose.

Among the SSAS systems, the major impact of the proactive schemes is the increase of network resilience and thus network usability. As indicated in Table 7.1, *Pro*-SSAS and SSAS+mRobot show the best performance. Maximum resilience (475 days) is obtained in the proactive mobile robot scheme where one- and two-hop nodes double their lifetime when replaced or rescued.

Table 7.1 - C-MAC: Design Metrics and Overall Network Performance

	C-MAC	SSAS	SSAS+ dRouting	SSAS+ dRouting	*Pro*-SSAS	SSAS+ mRobot
First node dies	291 s (121 days)	1571 s (655 days)	1831 s (763 days)	1921 s (800 days)	2344 s (977 days)	1721 s (717 days)
Usability	421 s (175 days)	1681 s (700 days)	2071 s (862 days)	2311 s (963 days)	2911 s (1213 days)	2861 s (1192 days)

However, the first dead node in SSAS+mRobot is a three-hop vulnerable one and thus cannot be rescued in the current implementation due to the limited service area of the robot (one and two hops neighbourhood). If the service area is enlarged, even better performance could be expected at the cost of higher requirements on the mobile robot's mobility. Design issues lie in the speed and trajectory of the robot, the interval between Battery Alert messages and the Battery threshold to start sending alerts at the non-vulnerable nodes. Assuming that the speed of the robot is fixed and low (<3m/s):

- the robot trajectory should be cyclic and optimised so that the delay between visits to the same regions is minimised,
- the interval between Alerts should be small enough to minimise the chances of a non-contacted robot crossing by (within the radio range),
- the Battery threshold below which nodes start the Alerts should be high enough to allow the robot to pass by at least once before the node actually dies.

In the current implementation, these issues are not a main concern to the most vulnerable nodes (BI>6) due that they start sending alerts at the beginning of the network lifetime, specifically after the 1st VCT (210s). However, since the initial battery is assumed 300 mA/s (to accelerate simulations) and attending to the average nodes' lifetime in the network without the Robot (i.e. the usability of SSAS in Table 7.1), the Battery threshold has been set to 110 mA·s which allows the node about 640s, the time that the robot requires to travel the square trajectory (640m long at 1m/s). With the addition that the interval between alerts is the same that the packet inter-arrival times, 20 s, most of the vulnerable nodes in range of the robot track are rescued.

Compared with SSAS, the routing alternatives significantly prolong the lifetime of the vulnerable nodes through dynamic routing and thus load sharing. The fact that sub-optimal routes (with respect to the initial shortest path routing) are used periodically leads to the slightly inferior data delivery at the first node dead time (i.e. the average data delivery registered before the first node dies). SSAS+dRouting2 improves the resilience over dRouting1 since load sharing is carried out at predetermined frames where the vulnerable nodes can remain sleeping to further enlarge their lifetime. Finally, *Pro*-SSAS maximises the network efficiency and outperforms the routing alternatives with similar results to SSAS+mRobot. Due to the scheduled access towards the vulnerable nodes, these nodes stay sleeping during the active periods, avoiding contention and consequent congestion problems at the traffic bottlenecks. Moreover the senders of the vulnerable nodes (those doing *Pro*-SSAS) only receive packets that results to a higher reduction of the amount of transmissions and derived congestion problems. Such benefits spread towards further hops (reflected in the BI drop of the whole network in Figure 7.6(b)) and accordingly the lifetime of network nodes, but not only the most vulnerable ones, is increased as shown in the Figure 7.7.

7.3.2.2 Average Performance Results

Simulations have been conducted in various randomly generated network topologies comprising 100 and 150 nodes in an area of 500m by 500m and 610m by 610m respectively, and significant improvements have been repeatedly observed. With topologies of 150 nodes a duty cycle of 1% is not sufficient and 2% was required to achieve a similar data delivery ratio (>90%). For brevity, the focus is restricted to the superior SSAS family. Table 7.2 lists the average performance results for the different alternatives and network sizes. The percentages of increase and decrease (-) with respect to the base solution SSAS are shown in parentheses.

Compared with SSAS, SSAS+dRouting1, SSAS+dRouting2, *Pro*-SSAS, and SSAS+mRobot prolong the lifetime of the most vulnerable node by from 14% to 45% respectively with 100 nodes, and from 9% to 36% respectively with 150 nodes. *Pro*-SSAS yields the best performance under this criterion. Additionally the proactive variants improve the network resilience by from 7% to 411% (100 nodes) or from 120% to 445% (150 nodes). Both *Pro*-SSAS and SSAS+mRobot append remarkable resilience of several times to SSAS. With regard to the network usability, again, 14% to 71% (100 nodes) or 21% to 80% (150 nodes) improvements are observed.

Table 7.2 – Proactive Schemes Comparison: Average values of performances

Schemes	First Node Die (days)	Resilience (days)	Usability (days)	Efficiency (Pkts/mAs)	ReTxon (%)
SSAS 100	622	107	736	36	37
SSAS+dRouting1 100	740 (19%)	114 (7%)	841 (14%)	40 (11%)	32 (-14%)
SSAS+dRouting2 100	772 (24%)	145 (36%)	917 (25%)	43 (19%)	31 (-16%)
Pro-SSAS 100	902 (45%)	268 (150%)	1140 (55%)	62 (72%)	7 (-81%)
SSAS+mRobot 100	709 (14%)	547 (411%)	1256 (71%)	55 (53%)	28 (-24%)
SSAS 150	349	44	393	34	47
SSAS+dRouting1 150	379 (9%)	97 (120%)	474 (21%)	38 (12%)	43 (-9%)
SSAS+dRouting2 150	400 (15%)	108 (145%)	507 (29%)	40 (18%)	43 (-9%)
Pro-SSAS 150	476 (36%)	240 (445%)	706 (80%)	51 (50%)	16 (-66%)
SSAS+mRobot 150	409 (17%)	222 (405%)	631 (61%)	44 (29%)	38 (-19%)

To further reveal the advantages in the proposed proactive schemes the additional performance criterion of energy-efficiency has been investigated. Here it is calculated with the values accumulated up to the resilience point (data delivery at sinks drops below 50%). This criterion reflects how fast the energy is depleted in the network in order to achieve the data delivery required (>90%). SSAS+dRouting variants improve the battery efficiency by from 11% to 19% whilst *Pro*-SSAS and SSAS+mRobot further advance the efficiency by 50% to 72%, and 29% to 53% respectively. The battery efficiency is calculated with respect to the average battery used at the resilience point, by when a number of nodes (fewer than 30) have already been rescued by the mobile robot in SSAS+mRobot. Virtually, these rescued nodes start a brand new life. This explains the high efficiency in SSAS+mRobot although from a long-term perspective the battery efficiency of SSAS+mRobot is basically the same as that of SSAS since the MAC operation is not changed. The benefits of

SSAS+mRobot are actually gained at the costs of the mobile robot. In contrast, the high efficiency of *Pro*-SSAS highlights again the important benefits of a carefully crafted hybrid MAC approach.

The last measurement included in Table 7.2 is the percentage of retransmissions (data packets retransmitted in the network per data packet received at the sink). Again this value has been calculated at the *resilience point*. Once the most vulnerable nodes start to die (between the first dead node time and the resilience point) the high amount of traffic that these were forwarding needs to be redirected to other neighbours in the baseline reactive re-routing. This situation aggravates congestion problems in the alternative routes and facilitates an important increase in the number of retransmissions. In the routing and robot schemes the reduction of retransmissions demonstrates the capacity to postpone the failure of the most vulnerable nodes. However, in *Pro*-SSAS, the high reduction is due to the collision-free access at vulnerable nodes after the VCTs. From other point of view, retransmissions "before" the first node dies compared to the base approach SSAS is, equal in SSAS+mRobot, slightly inferior in SSAS+dRouting1 and SSAS+dRouting2, but significantly lower in *Pro*-SSAS.

In addition, it is worth mentioning that the mean packet delivery delays in the SSAS *variants* are comparable with those in SSAS and in the order of 20 s. In SSAS+dRouting, delays are increased as expected compared with SSAS since sub-optimal routes are applied from time to time. Nevertheless, the delay increases seem tolerable (between 5% and 20% higher than SSAS). After the first nodes start to die the delays are notably increased as a result of re-routing and congestion added in the alternative routing trees. The impact is approximately proportional to the amount of traffic that the dead nodes were forwarding. The proactive schemes that achieve higher resilience, *Pro*-SSAS and SSAS+mRobot, manage to rescue the most vulnerable nodes (traffic bottlenecks) and thus smaller delay increases are found after nodes start to die.

7.4 Summary

Failure management is crucial in resource-constrained wireless sensor networks to sustain the network usability. Effective local metrics are needed to enable self-directed reactive or proactive failure recovery or prevention schemes. Prediction-based proactive solutions are preferred to be initiated before the system suffers from node failure.

The detection of failure-prone nodes is effectively achieved through the Battery Index (*BI*) that enables accurate evaluation of how fast the node energy is consumed. Subsequently, three *BI*-enabled cross-layer proactive schemes have been co-designed to circumvent the network vulnerability through scheduling access with hybrid MACs, load sharing with dynamic routing or node rescue with the help of intelligent mobile robots. The *BI* threshold which recognises a vulnerable node has been investigated to identify only the most vulnerable nodes and hence balance the implications of an extensive application of the proactive schemes.

Simulation results have validated the effectiveness of the *BI* metric and demonstrated improved performances when the proposed proactive schemes are applied in terms of significantly prolonged lifetime of first node to die (up to 45%), enhanced network resilience (up to 445%), increased network usability (up to 80%) and improved battery efficiency (up to 72%). Hence these schemes seem promising to further significantly increase the battery efficiency and thus node lifetime in SSAS-based networks. In particular, the network usability and efficiency in *Pro-SSAS* is especially increased without the need of nodes replacement, which highlights the importance of an effective radio access mechanism.

In addition, it is noted that the independently proposed proactive schemes could be applied jointly. Merged solutions and more context-aware adaptive schemes can be investigated in future work.

Chapter 8

Discussion

The co-design process of the cross-layer developments inside the XLCA architecture shows the upward trend of the longevity improvements achieved in the chain of solutions proposed: C-MAC → *Dir*C-MAC → SSAS OD → SSAS_*nSectors* → SSAS+dRouting → SSAS+mRobot → *Pro*-SSAS.

The introduction of switched beam antennas in the contention access in *Dir*C-MAC shows a significant reduction of congestion problems in the entire network, which translates in the ability to increase by more than double the lifetime and energy-efficiency with respect to the base scheduled contention C-MAC (Table 5.3).

The adoption of sink localised hybrid access in SSAS significantly reduces the funnelling effect typical in nodes-to-sink multi-hop networks; accordingly SSAS achieves, for example between three to seven times higher lifetime compared to C-MAC with an OD and an eight Sectors antennas respectively (Figure 6.9).

The proactive schemes proposed in SSAS manage to extend the lifetime of the most energy-vulnerable nodes and, as a result, the network lifetime in terms of usability is increased with respect to SSAS a 21% in SSAS+dRouting1, 29% in SSAS+dRouting2, 61% in SSAS+mRobot, and 80% in *Pro*-SSAS (Table 7.2).

Figure 8.1 represents, qualitatively, the incremental improvements of the operational network lifetime that the results in Chapters Chapter 5 , Chapter 6 and Chapter 7 have shown in several scenarios and different application requirements. The slotted line represents the solutions of other authors that have been implemented inside the XLCA for comparison purposes. In a nodes-to-sink application with periodic traffic and the requirement of data delivery ratio at the sink over 90%, the implementation of solutions from left (B-MAC) to right (SSAS_8) will achieve higher efficiency and as a result an increasing network operational lifetime. The solutions inside the brackets obtain higher efficiency with increasing number of sectors of the switched beam antennas, which are mounted in every node (*Dir*C-MAC) or in the sink (SSAS). The proactive schemes that have been evaluated in SSAS OD attain considerably different lifetime improvements, qualitatively indicated in Figure 8.1, being *Pro*-SSAS the best proactive scheme to circumvent nodes vulnerability and extend the network usability.

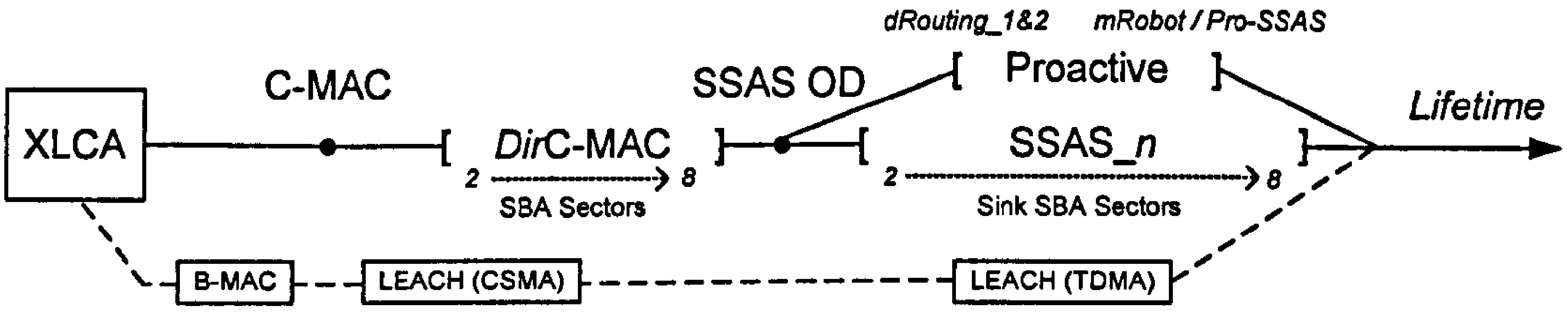

Figure 8.1 – Qualitative representation of lifetime improvements

8.1 Reflection on the Research Context of DIAS

In line with the DIAS Co-Design objective, this thesis has dealt with the Co-Design aspects on the impact of "dynamic communications" as a methodology to devise communications protocols in increasingly considered large sensor networks applications. Due to the network variability and nodes constraints typical of WSNs explained in Section 3.1.2, the form in which this co-design has taken place in this research does not consider the definition of analytical cost functions in the design of the pre-deployment architecture envisioned in DIAS (Section 1.5.2). Alternatively the approach has focused on the integration of the communication elements (Figure 3.1) inside the cross-layer framework XLCA, which has been exercised for the post-deployment co-design and assessment of novel adaptive cross-layer techniques in WSNs. The post-deployment adaptability contributes to the global cost-function, a *posteriori*, longevity with the prolongation of the operational network lifetime. Additional work would attempt to merge this into an a *priori* pre-deployment co-design feature.

The XLCA provides a tool for the co-design, adaptation and assessment of cross-layer communication solutions. An overriding consideration has been the network longevity, and has been achieved through the integration (co-design) of the various elements participant in the communications process (Routing-MAC-Physical) and the use of novel techniques in WSNs such as directional antennas, hybrid access mechanisms and pro-active schemes.

In addition the co-design approach has focused in the performance improvement of both the general network (e.g. directional antennas in DirC-MAC, hybrid MAC in SSAS) and the individual node (e.g. adaptive sleeping or proactive schemes at vulnerable node). At the end, combination of both solutions target the same purpose of this research, adapt network communications in order to extend the operational network lifetime of large wireless sensor networks (objective of DIAS).

8.2 Findings

This section describes important findings that can be extracted from the assessment of the techniques and models that have been proposed in this thesis. These findings can be classified by the different solutions presented in Chapters Chapter 5 Chapter 6 and Chapter 7 .

8.2.1 DirC-MAC

The development of *Dir*C-MAC to improve the OD contention access in C-MAC explained in Chapter 5 illustrates the **co-design process** that has been used in this research. This process starts with the **assessment of several congestion metrics** (collisions, retransmissions, overhearing packets, etc) of C-MAC and is followed by the identification of the network conditions and interactions between nodes that have promoted such congestion results. Then the use of directional antennas is proposed, which requires a prior study of the needs, implications and design problems that its implementation has in sensor networks. Subsequently realistic models are applied to the design of the proposed switched beam antennas, which allows the design of the directional handshaking mechanisms and associated Tx power control to optimise the use of such antennas. In this manner, the directional problems that theory provides (those explained in 5.2.3) are actually checked in the simulation results, such as the increasing number of collision with higher gain antennas (*Dir*C-MAC 8) illustrated in Table 5.3. The results indicate that a realistic modelling of directional antennas is crucial. For instance, adoption of a flat-top directional antenna model with beam gain modelled as a solid segment (constant maximum gain in the sector $= \frac{360^o}{\text{Sectors}}$) and null side-lobes can double the energy-efficiency of *Dir*C-MAC in the simulation results with respect to the double-Gaussian beam and ball model that has been used (Section 4.1.8).

The **power reduction** in *Dir*C-MAC is not mainly caused by the lower Tx power with directional antennas, but by the congestion reduction that allows to decrease the duty-cycle within the adaptive MAC schemes provided. The directional antennas were proposed as means of adaptation against interference problem and, this adaptability turns into network longevity.

Analysis of the results in Figure 5.17 comparing different **handshaking techniques** on *Dir*C-MAC gives a better understanding of the tradeoffs using directional transmissions, especially between throughput improvements due to spatial reuse, and power reduction, attributable to the higher Idle state with increasing amount of NAV scheduled. The realistic modelling assumptions illustrate the limitations of the two-way handshaking mechanism (DA) and evidence the importance of the use of control packets with directional antennas in order to enable directional beam-forming in reception and avoid hidden terminal problems. Indeed the use of the CTS packet in the four-way handshaking is justified up to 4 sectors antennas in Figure 5.17 after the inform Beacon approach, which rescind the use of CTS, starts to dominate the data delivery rate over the base 4-way handshaking mechanism in *Dir*C-MAC.

Antenna design. Figure 5.16 andTable 5.4 show the significant improvement with the use of switched beam antennas of only 3 sectors that permits a doubling of the lifetime with respect to the OD C-MAC. Alternatively, 2.87 times higher lifetime is obtained with 8 sectors. This indicate that the requirements in gain, thus antenna directivity (Beamwidth), are feasible regarding the current antenna technologies, such as the MaxBeam [79] antenna. While its incorporation in every node of the network may not be affordable, the significant improvements of SSAS results with SBAs mounted at the sinks (Figure 6.15) encourages the use of SBA technology at sinks with conjunction of adaptive hybrid MAC techniques to maximise the performance.

8.2.2 SSAS

The various results showed in Chapter 6 highlight the distinctive feature in SSAS, the **ability to decrease duty-cycle.** Table 6.2 demonstrates the ability of SSAS to reduce duty-cycles from 5 (C-MAC) to 0.5 (SSAS 8) and achieve the same application requirements. This translates in up to 6.7 times higher lifetime in SSAS_8 with respect to C-MAC.

The **adaptability** in SSAS has been probed with the extensive performance evaluation of SSAS in Chapter 6 (Sections 6.3.2 to 6.3.8) under a wide range of scenarios and application requirements. The results show the capacity of the localised hybrid access, adaptive schemes included and the use of switched beam antennas at the sink in order to adapt the network operation regarding the traffic and congestion conditions.

The performance evaluation analysed in these sections illustrate the non-parallelism of **energy-efficiency** and lifetime in SSAS, for example:

Figure 6.7(b): 100 nodes – 25 sources – 1Pkt/400s → 3200 days and 2 Pkts/mA·s

Figure 6.10: 100 nodes – 100 sources – 1Pkt/20s → 1050 days and 34 Pkts/mA·s

Looking at the improvements of SSAS in Figure 6.11 with higher data-rates and also the improvements shown in Figure 6.13 with higher number of sources, it is concluded that SSAS offers higher energy-efficiency with increasing traffic in the network for the same number of nodes. This is only true if the maximum network capacity is not reached (i.e. situation of congestion collapse explained in 6.3.4). From the SSAS results, it is patent the high capacity that SSAS has to adapt the nodes operation (duty-cycle with the *Adaptive Sleeping* explained in 6.2.2) to the traffic conditions and to minimise congestion problems with the hybrid access approach.

The benefits of SSAS, thus its applicability, do not only come with high traffic and congestion conditions. With very low data rate scenarios (6.3.2.2) SSAS is yet more efficient than C-MAC or B-MAC.

Section 1.2 has listed several application examples in different domains. In many of these applications (e.g. sensor nodes located at the containers in a harbour) the **density** of nodes can be significant with, for example, an average of five or more Neighbours per Node (Avg.NpN) in the network. The results in 6.3.7 show how the hybrid access in SSAS and the extension of the one-hop neighbourhood area with switched beam antennas on the sink cope with the ability to maintain the application requirements, and even improve the efficiency (see Figure 6.14) when the density of nodes, thus traffic load, increases. For instance, in the same deployment area of 650m x 650m, SSAS_8 raises the network efficiency (Pkts/mA·s) from 50 to 129 when the number of nodes in the network increases from 100 (Avg.NpN = 4) to 500 (Avg.NpN = 23). Afterwards the efficiency decreases because the high traffic intensity that make the network to reach a congestion collapse [105] state due to the high congestion and buffer overflows.

When SSAS performance is limited as a result of the high traffic with increasing network size, data rate, number of sources or density, a straightforward solution supposes the addition of extra sinks. Thanks to the localised hybrid access on the sinks, the improvements of **additional sinks** in the network are very significant as illustrated in Figure 6.15. These benefits, again, are maximised with the increasing directivity (gain and range) of the SBA mounted in the sinks. A huge performance gap is revealed in Figure 6.15, with 7 times higher energy-efficiency and 11 times lower delay in SSAS_8 (5 sinks) compared with SSAS_OD (1 sink).

It has been noticed that with several sinks fairly distributed and the use of SBAs on the sinks to increase the one-hop area, it is possible to converge to a **full TDMA** approach (one-hop network) where there is no need of active time as every node is in range of the sink, and thus lifetime is optimal. However this scenario is not realistic in large networks where multi-hop is a must, and neither desired in most of the applications that have been considered in Chapter 1 as the WSN loose the essence of having a share channel to collaborate in the sensing tasks, enable scalability of topology changes or nodes mobility and detection of events via radio overhearing.

A main concern for the design of proactive failure management schemes has been the **non-uniformity battery usage.** The Coefficient of Variation obtained in 6.3.2.2 comparing SSAS (8%), C-MAC (21%) and B-MAC (63%) highlights that in SSAS, the variance between different hop neighbourhoods is maintained respect the variance of the whole network, and inside each neighbourhood is decreased up to 3 and 6 times compared to C-MAC and B-MAC respectively. This illustrates the SSAS effectiveness in the reduction of congestion, which decrease the idle listening, retransmissions and collisions compared to C-MAC.

In C-MAC, DirC-MAC and SSAS, **latency** in the data delivery is a direct consequence of the delay elapsed between the data generation instant and the active time in which the packets are actually delivered. If packets are generated just before the active time, and providing that the duty-cycle is big enough, the delay acquisition is almost negligible, as illustrated in the SSAS results of Figure 6.15 with delays as low as 1s with an inter-packet arrival time of 20s.

8.2.3 Proactive Schemes

In the **co-design** of the proactive schemes proposed in Chapter 7 , a first step has been the analysis of the particular circumstances in several scenarios that promote the existence of the most vulnerable nodes. This analysis has served to identify a discovery procedure to assess nodes vulnerability with proven suitability in various network scenarios and traffic rates. In order to co-design effective schemes, the tradeoffs derived from the implementation of such schemes when changing the network conditions have been also considered and verified; for example the use of suboptimal routes in the dynamic routing approaches.

Among the proactive schemes proposed, ***Pro*-SSAS** is the most elaborated scheme; it manages to circumvent nodes vulnerability state, and in addition achieves the enhancement of the entire network performance with a further reduction of the congestion and funnelling effect with respect to SSAS. *Pro*-SSAS, triggered at the vulnerability checking times (Figure 7.1) enables a local swapping towards a hybrid access at the autonomously detected vulnerable nodes. The mechanism that initiates *Pro*-SSAS has been designed to maximise the success of the exchange on the access control and to incur minimum overhead. Nevertheless *Pro*-SSAS, and also the dynamic routing solutions, are reversible, with the control residing in the vulnerable node that decides to trigger the proactive scheme.

The results in Table 7.2 highlight the benefits of Pro-SSAS that always obtains the highest lifetime of the first node to die, which are actually the remaining most vulnerable nodes after the hybrid access has been triggered at the initially most vulnerable nodes (10%). Moreover, *Pro*-SSAS manages to outperform the mRobot without need of replacing nodes and obtains higher performance improvements with respect to SSAS when higher number of nodes is considered in Table 7.2. With increasing multi-hop communications, the most vulnerable nodes register higher data traffic and the benefits of executing Pro-SSAS are more significant in the network overall performance. Indeed the network usability is extended up to 80% compared to the base SSAS approach (Table 7.2).

The implementation of **dRouting2** mechanism is an example of the combination (co-design) of Routing and MAC techniques in a single solution. As indicated in the Section 2.5 (state of the art), reactive and proactive routing has been the main methodology used for failure management. Despite the fact that routing mechanisms are widely used in traditional fixed and wireless networks with proven effectiveness, the results obtained in this thesis promote the use of adaptive MAC techniques, such as *Pro*-SSAS. Because of the energy constraints, a main difference in sensor networks with other wireless networks is the limitation of time provided for establishing communications and route the packets to the collection points. This restriction encourages the concentration of communications in short spaces of time-sharing to minimise the expenditure of energy. This increases the level of contention and the unavoidable funnelling effect in nodes-to-sink multi-hop applications which limits the benefits of the balancing dynamic routing strategies, such as dRouting 1 & 2 (Figure 7.7). In any case, the improvements of the dRouting alternatives are yet significant as illustrated in Table 7.2. Nevertheless, the success of the dynamic routing schemes requires network **redundancy** (nodes density) to actually provide alternative routes. Moreover, it has been shown that the proactive routing schemes, while achieving its purpose of extending lifetime of vulnerable nodes, also attain smaller data delivery (~5% less) at the sinks as shown in Figure 7.7 with respect to the original shortest path/minimum distance routing in XLCA. Dynamic routing is a balance technique and the congestion problems derived from the traffic load are passed to alternative neighbours. It can be noted that these nodes were dismissed in a first instance during the initialisation as they didn't provide the **stronger link** towards the sink. This supports the idea introduced in 1.4.2 of selecting neighbours with stronger links and do not adjust Tx power to the link range in networks where density and multi-hop communications compromise the existence of an interference-free radio channel.

The success of the **mobile Robot** (SSAS+mRobot) to extend network usability lies in the ability of replacing vulnerable nodes, which is equivalent to increase by double the battery level of these nodes or to place a backup node at the beginning of the network lifetime besides the most vulnerable nodes. This fact encourages, if the use of robots is not feasible in specific applications, the increase of node redundancy at pre-deployment time in the a *priori* expected hot-spots (areas with higher traffic intensity). However, the vulnerability among nodes in the network cannot be assessed in advance at randomly deployed sensor networks. In any case, a mechanism as the proposed in the mRobot (7.2.3) becomes necessary to actually activate a backup node after its associated vulnerable nodes has come to the end. On the other hand, if the purpose is to use backup nodes to balance traffic load with the vulnerable nodes, mechanisms such those proposed in dRouting2 are suitable.

8.3 Evaluation of Validity Threats

The results offered in this research were obtained through extensive simulations whose validity is based on appropriate modelling and integration of the different elements involved in the communication system. The relevance of the improvements that the co-designed adaptive techniques provide in the area of sensor networks is based on comparison with the non-adaptive base solutions (C-MAC), and with other protocols such as LEACH and B-MAC. Important remarks for the internal and external validation of the simulation results are described in this section.

8.3.1 Internal Validity – Models

The modelling methodology in this thesis has tried to comply with the communication processes that occur in real sensor network environments. The proper functioning of each layer of the architecture XLCA implemented in OMNeT++ has been checked and confirmed during the evaluation of the solutions proposed in Chapters Chapter 5 , Chapter 6 and Chapter 7 . The procedure used to verify the models has been explained in 4.2.3, the effectiveness of which is based in the modular concept and hierarchy of the simulation framework. As indicated in the 8.2, the performance modelling adopted illustrates via simulation the dependency of the MAC performance on radio channel characteristics, transceiver operation and antenna radiation pattern assumptions.

The problems derived from congestion and the funnelling effect in multi-hop networks, which have been considered by several authors, as explained in 1.4, have been detected in all the scenarios considered. The extent of these problems, as expected, is proportional to the network size, density, number of sources and traffic generated. The realistic modelling of the switched beam antennas have allowed tradeoffs of its use in contention environments, which have directed the design of the MAC mechanisms to control them.

In addition, the use of the additive interference model explained in 4.1.7.3 permits to detect the occurrence of link failures, thus loss of packets (signal under the SNIR threshold). These problems were already expected from the experimental research in this area that has been introduced in 1.4.2. However, it should be noted that the physical models (transceiver, antenna and mainly the radio channel) are approximations and cannot adjust closely the particular conditions of each of the practical scenarios. An accurate validation of the results that have been shown in this thesis will require experimental results with the use of a WSN test bed.

8.3.2 External Validity - Comparisons

In order to reflect the actual improvements of the solutions proposed in this research, the pure-contention C-MAC (4.1.4), the polling access B-MAC [28] and the TDMA-like protocol LEACH [29] have been implemented and compared within the XLCA simulation framework. The results in Chapters Chapter 5 , Chapter 6 and Chapter 7 have shown important improvements with respect to these solutions, which are qualitatively represented in Figure 8.1. The major enhancement of the XLCA is the hybrid MAC SSAS that has been able to outperform the idealistic LEACH protocol (assumptions in 4.3.1) in various scenarios presented in the Chapter 6 results.

On the other hand all the proposed protocols, including C-MAC, are able to significantly exceed the performance of B-MAC (see Figure 6.8). These results have highlighted the inefficiency of a polling MAC in monitoring applications with periodic reports. In Figure 6.7(a), with only 25% of nodes of the network being sources, SSAS OD (without SBA on the sink) achieves ten times more efficiency.

In addition, B-MAC is the base access mechanism in several hybrid protocols, such as Z-MAC [72] and Funneling-MAC [30] (explained in 2.3.1). Although these MACs have not been implemented within the XLCA, there are several considerations that predict significant improvements in energy efficiency of the protocol SSAS with respect to such hybrid MACs. The results in [30] show better performance for Funnelling-MAC than Z-MAC. However with high traffic or number of sources, the performance of both solutions tends to converge towards B-MAC. Also the packet loss rate in Funneling-MAC is higher than 40% [30] in the one-hop nodes even with the TDMA approach. When the network is saturated, authors in [30] conclude that the optimal path depth is of one hop, meaning that only the direct neighbours to the sinks use TDMA for transmitting their packets. Alternatively SSAS offers null loss rate at one-hop nodes and takes advantage of the directional antenna capabilities to increase the number of one-hop neighbours to the sinks which benefit from the TDMA scheduling. As a result, the congestion at the nodes near the sinks (funnelling) are highly mitigated compared with pure contention solutions such as C-MAC or B-MAC (see 6.3.2).

Chapter 9

Conclusion

In Wireless Sensor Networks the sensor nodes interact closely with the physical environment in which they reside. These networks must be designed to effectively deal with the network's dynamically changing conditions and resources, including energy of the nodes and traffic load. Furthermore, sensor networks have to deal with the adverse effects of node failures and link disruptions in uncertain and dynamic physical environments. Because of these challenges the introduction of post-deployment adaptability is a primary design goal that, in many cases in the current state of the art, has been a secondary add-on. The cross-layer techniques that have been proposed in this thesis can help to maintain the required WSN QoS (application requirements) in the event of congestion problems and node failures and, as a result, the network longevity is enhanced. In order to design resilient sensor networks, the solutions in this thesis encourage the use of post-deployment mechanisms, where nodes autonomously change their configuration as required and run algorithms that are optimised for node survivability and energy usage.

Although the inclusion of these adaptive techniques in WSN will incur higher complexity of the nodes in terms of code and processing, the benefits of the adaptive solutions in order to optimise the use of radio resources and preserve the application requirements are well worth. Nevertheless, due to the latest advances in computation technology, the energy cost of using the CPU resources are insignificant compared with those of the radio devise.

9.1 Conclusions

- The Co-Design methodology promoted in the DIAS project (Section 1.5), and particularly that based on the communications aspects of WSNs (Chapter 3), is an effective method for the design of cross-layer wireless communication protocols.
- Parallel to the need for low-power wireless hardware, the design of adaptive energy-efficient MACs is one of the greatest challenges to the viability of many of the sensor network applications that are emerging.
- Adaptive MACs with functionality designed to deal with the demands of different applications and to handle network dynamics are necessary in WSNs because of the variability of the environment and operation conditions.
- The adaptability of the network under changing conditions is not at odds with the need to minimise energy expenditure. This is evidenced by the increased energy efficiency of the adaptive and proactive solutions in this research.
- The co-designed communications solutions proposed have accomplished the most important objective of this thesis: extension of the operational life of WSNs on which the established requirements are preserved.
- The co-design of contention MACs with the introduction of directional antennas enhances the diversity in medium access and reduces congestion problems in sensor networks.
- The use of switched beam antennas at the sinks with scheduled sectorial access in the hybrid SSAS is shown as a potent access mechanism to improve the network operational lifetime in nodes-to-sinks applications.
- The integration of Routing and hybrid MACs with cross-layer information exchange enables the design of efficient and autonomously initiated proactive schemes to circumvent energy vulnerability of nodes in multi-hop sensor networks.

9.2 Summary of Contributions

During the development of the present work, several contributions and achievements were made. The main contributions are:

- the modelling and implementation of XLCA as a framework for the co-design and assessment of cross-layer techniques that can make use of directional antennas and different physical (transceiver and channel) parameters,
- the development and assessment of adaptive MACs,
- the integration of energy saving technologies such as switched beam directional antennas that effectively reduce congestion problems,
- the development of the hybrid MAC SSAS which significantly improves network longevity and,
- the devising of locally initiated proactive schemes that successfully have extended the energy-vulnerable nodes lifetime, but also the entire network longevity.

These research contributions have led to a series of publications that are indicated in Appendix B: Papers Published from this Work.

9.3 Future Research

There is still much work to be done in the area of protocols for wireless sensor networks. The protocols developed in this research have focused on multi-hop scenarios where the sensors have correlated data and nodes can adapt to the varying traffic of such scenarios only. However, there are important applications of WSNs where this is not the case. For example, sensor networks for medical monitoring applications may have different sensors located on and/or in the body to monitor vital signs. These networks will not be as large-scale as the ones discussed in this thesis, but they will have similar requirements – long system lifetime, low-latency data transfers, and adaptability to network dynamics. However these networks will most likely focus on maximising quality above all, and loss of information will not be acceptable. Implementation of this kind of application within the XLCA framework will require support for QoS issues along with the unique considerations of these networks.

An additional future work with many important applications is the consideration of indoor environments such as WSN in smart buildings. This will require the extension of XLCA with the adaptation of the PHY models and the design of new MACs.

The adaptability skills included in the XLCA with adaptive MAC that profits overhearing of neighbours allows the existence of mobile nodes in the network, providing that a fixed structure remains to forward the data towards the sink. In some applications the sinks are mobile, carried by a user, vehicle or animal, and an initial investigation was performed inside the XLCA to develop fast routing schemes triggered at the mobile sink to allow multi-hop data collection with minimal duty-cycle requirements. These techniques have not been fully developed and may be carried on in future research. In addition, the XLCA framework and already implemented functionality, is seen as a useful tool for the design and assessment of new techniques to be proposed in the area of sensor networks.

Finally and most importantly, an appealing future work will consist of the integration of the communications solutions proposed in this thesis with the rest of the DIAS-MC areas of co-design (see 1.5.1). The aim will be to integrate the pre-deployment design of HW and SW solutions with the post-deployment adaptability developments that have been investigated in this research.

References

[1] 10 Emerging Technologies that will change the world: Wireless Sensor Networks, in MIT's Magazine of Innovation, Technology Review, February 2003, pp. 2. [Online]

[2] (2009) EPSRC DIAS project. [Online]. Available: http://www.dcs.gla.ac.uk/dias/

[3] C. C. Enz, N. Scolari, and U. Yodprasit, "Ultra Low-Power Radio Design for Wireless Sensor Networks," in IEEE Int. Work. on RF Integration Technology, *Dec. 2005, pp. 1-17.*

[4] (2009) Berkeley Wireless Research Center *(BWRC). [Online]. Available: http://bwrc.eecs.berkeley.edu/*

[5] B. Cook, "Low energy RF transceiver design," Ph.D. dissertation, University of California, Berkeley, 2007.

[6] D. Steingart, S. Roundy, P. Wright, and J. W. Evans, "Micropower materials development for wireless sensor networks," Materials Research Society (MRS) Bulletin, Apr. 2008, vol. 33, no. 4, pp. 408-409.

[7] D. Steingart, C. C. Ho, J. Salminen, J. W. Evans, and P. Wright, "Dispenser printing of solid polymer-ionic liquid electrolyte for lithium ion cells," in IEEE International Conference on Polymers and Adhesives in Microelectronics and Photonics (Polytronics 2007), Jan. 2007, pp. 261-264.

[8] P. Rashidi, M. Youngblood, D. J. Cook, and S. K. Das, "Inhabitant Guidance of Smart Environments," Proceedings of HCI, July 2007, Vol. 2, pp. 910-919.

[9] D. J. Cook and S. K. Das, Smart Environments: Technology, Protocols and Applications, John Wiley, 2004. ISBN 0-471-54448-5.

[10] I. W. Marshall, M. C. Price, H. Li, N. Boyd, and S. Boult, "Multi-sensor Cross Correlation for Alarm Generation in a Deployed Sensor Network," in EuroSSC 2007, 2007, pp. 286–299.

[11] SECOAS Project. Marine monitoring. [Online]. Available: www. secoas.org

[12] K. H. Kwong, T. T.Wu, H.G. Goh, B.Stephen, M. Gilroy, C. Michie, and I.Andonovic, "Wireless Sensor Networks in Agriculture: Cattle Monitoring for Farming Industries", Progress In Electromagnetics Research Symposium (PIERS), 23-27 March 2009, Beijing, China.

[13] K. Sasloglou, I. A. Glover, K. H. Kwong, I. Andonovic, "Wireless sensor network for animal monitoring using both antenna and base-station diversity", in Communication Systems, 2008. ICCS 2008. 11th IEEE Singapore International Conference , Guangzhou, China, Nov. 2008, pp. 27-33.

[14] R. Szewczyk, A. Mainwaring, J. Polastre, and D. Culler. An analysis of a large scale habitat monitoring application. In Proc. Second ACM Conference on Embedded Networked Sensor Systems, SenSys'04, Nov. 2004.

[15] M. Hefeeda, M. Bagheri, M. "Wireless Sensor Networks for Early Detection of Forest Fires", In Proc. of International *Workshop on Mobile* Ad hoc and Sensor Systems for Global and Homeland Security (MASS-GHS 07), Pisa, Italy, Oct. 2007, pp.1-6.

[16] M. Fraser, A. Elgamal, L. Yan, and J. P. Conte. "Video and Motion Sensor-Network for Bridge Monitoring Applications," in Proc. of the 4 th World Conference on Structural Control and Monitoring, University of California, San Diego, Jul. 2006.

[17] D. Lee, B.Park, B. Paik, S. Cho, J. Choi, H. Kang, Y. Kim. "Use of Sensor Network for Real-time Monitoring Systems in Ships and Offshore Structures", in Proc. of the Eighteenth International Offshore and Polar Engineering Conference Vancouver, BC, Canada, Jul. 2008.

[18] R. Adler, P. Buonadonna et al. "Design and deployment of industrial sensor networks: Experiences from the north sea and a semiconductor plant". In Proc. of the 3rd ACM Conference on Embedded Networked Sensor Systems, SenSys '05, San Diego, California, USA, Nov. 2005, pp. 64-75.

[19] L. Gu, D. Jia et al. "Lightweight detection and classification for wireless sensor networks in realistic environments". In Proc. of the 3rd ACM Conference on Embedded Networked Sensor Systems, SenSys '05, San Diego, California, USA, Nov. 2005, pp. 157–182.

[20] J. Aslam, Z. Butler, F. Constantin, V. Crespi, G. Cybenko, and D. Rus, "Tracking a moving object with a binary sensor network". In Proc. First ACM Conference on Embedded Networked Sensor Systems, SenSys '03, 2003, pp. 150–161.

[21] L.W. Yeh, Y.C. Wang, and Y.C. Tseng, "iPower: an energy conservation system for intelligent buildings by wireless sensor networks". International Journal of Sensor Networks Volume 5, Issue 1. Feb. 2009, pp. 1–10.

[22] N. Ota, S. Ahrens, A. Redfern, P. Wright, and X. Yang, "An application-driven architecture for residential energy management with wireless sensor networks," in IEEE International Conference on Mobile Adhoc and Sensor Systems, Oct. 2006, pp. 639-644.

[23] B. Zhou, A.Marshall, W. Zhou, T.H. Lee, "Novel Wireless Mesh Networking Architectures for Future Smart Homes," in Future Generation Communication and Networking (FGCN 2007), pp. 43-48.

[24] (2009) CodeBlue: Wireless Sensors for Medical Care. Harvard Sensor Network Lab. [Online]. Available: http://fiji.eecs.harvard.edu/CodeBlue

[25] A. Hande, T. Polk, W. Walker, and D. Bhatia, "Self-Powered Wireless Sensor Networks for Remote Patient Monitoring in Hospitals", Sensors, Vol.6, Issue.9, pp.1102-1117, 2006.

[26] V. Shnayder, M. Hempstead, B. Chen, G. W. Allen, and M. Welsh, “Simulating the power consumption of large-scale sensor network applications,” in Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems, SenSys'04, pp. 188–200, Baltimore, Md, USA, Nov. 2004.

[27] W. Ye, J. Heidemann, and D. Estrin. “An energy- efficient MAC protocol for wireless sensor networks”. In 21st Conf. of the IEEE Computer and Communications Soc. (INFOCOM), Jun. 2002.

[28] Polastre, R. Szewczyk, D. Culler, and. J. Anderson, “Versatile Low Power Media Access for Wireless Sensor Networks”. In Proc. ACM Conference on Embedded Networked Sensor Systems, SenSys'04, 2004

[29] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-Efficient Communication Protocol for Wireless Microsensor Networks,” Proceedings of the 33rd Hawaii International Conference on System Sciences (HICSS ’00), Jan. 2000.

[30] Gahng-Seop Ahn, Emiliano Miluzzo, Andrew T. Campbell, Se Gi Hong, F. Cuomo, “Funneling-MAC: A Localized, Sink-Oriented MAC for Boosting Fidelity in Sensor Networks”. In Proc. ACM Conference on Embedded Networked Sensor Systems, SenSys'06, 2006.

[31] B. O. Priscilla Chen and E. Callaway, “Energy Efficient System Design with Optimum Transmission Range for Wireless Ad-Hoc Networks”, in Proc. of ICC, vol. 2, 2002, pp. 945.952.

[32] J. Haapola, Z. Shelby, C. Pomalaza-Raez, and P. Mahonen, “Cross-layer energy analysis of multihop wireless sensor networks,” in Proceeedings of the 2nd European Workshop on Wireless Sensor Networks (EWSN '05), pp. 33–44, Istanbul, Turkey, Jan. 2005.

[33] S. L. Willis and C. J. Kikkert, "Radio propagation model for long-range wireless sensor networks," in Proc. of the 6th International Conference on Information, Communications & Signal Processing, Dec. 2007, pp. 1-5.

[34] (2009) Crossbow Technology: Wireless Sensor Networks: Home Page [Online]. Available: http://www.xbow.com/Home/HomePage.aspx

[35] F. Darbari, K. Sasloglou, R.W. Stewart, I. A. Glover and I. Andonovic, “Effect of Antenna Height and Polarisation on Short Wireless Sinks”, in Proc. Of the 16th European Signal Processing Conference, EUSIPCO 2008.

[36] (2009) Speckned Project: [Online] www.specknet.org

[37] H. EdgarH, Jr. Callaway, "Wireless Sensor Networks, Architectures and Protocols", Auerbach Publications. 1st edition, Aug. 2003.

[38] A. Boulis, S. Ganeriwal, and M.B. Srivastava. “Aggregation in Sensor Networks: An Energy-Accuracy Trade-off”. In Proc. of the First IEEE International Workshop on Sensor Network Protocols and Applications (SNPA'03), 11 May 2003.

[39] Y.C. Wang, Y.Y. Hsieh, and Y.C. Tseng, "Compression and Storage Schemes in a Sensor Network with Spatial and Temporal Coding Techniques", IEEE Vehicular Technology Conference (VTC-Spring), 2008, pp. 148-152.

[40] Jeremy Elson. "Time synchronization in wireless sensor networks", Ph.D. dissertation, University of California, May 2003.

[41] T. Schmid, J.Friedman, Z. M. Charbiwala, Y. H. Cho, M. B. Srivastava, "XCXO: An Ultra-low Cost Ultra-high Accuracy Clock System for Wireless Sensor Networks in Harsh Remote Outdoor Environments," ISSCC/DAC 2008, Feb. 2008.

[42] S. Ganeriwal, R. Kumar, and M. B. Srivastava, "Timing-sync protocol for sensor networks," in Proc. of the 1st International Conference on Embedded Networked Sensor Systems (SenSys '03), Nov. 2003, pp. 138–149.

[43] (2009) Chipcon CC2420 and CC2520 datasheets. [Online]. Available: http://www.chipcon.com

[44] T. V. Dam and K. Langendoen, "An Adaptive Energy-Efficient MAC Protocol for Wireless Sensor Networks". In In Proc. ACM Conference on Embedded Networked Sensor Systems, SenSys'03, Los Angeles, 2003, pp.171-180.

[45] K. Sha and W. Shi, "Revisiting the lifetime of wireless sensor networks," in SenSys '04: Proceedings of the 2nd international conference on Embedded networked sensor systems. New York, NY, USA: ACM Press, 2004, pp. 299–300.

[46] G.-S. Ahn, S. G. Hong, E. Miluzzo, A. T. Campbell, and F. Cuomo, "Funneling-mac: a localized, sink-oriented mac for boosting fidelity in sensor networks," in SenSys '06: Proceedings of the 4th international conference on Embedded networked sensor systems. New York, NY, USA: ACM Press, 2006, pp. 293–306.

[47] K. Srinivasan, P. Dutta, A. Tavakoli, and P. Levis, "Understanding the causes of packet delivery success and failure in dense wireless sensor networks," Proceedings of the 4th international conference on Embedded networked sensor systems, pp. 419-420, 2006.

[48] J. Zhao and R. Govindan. "Understanding packet delivery performance in dense wireless sensor networks". In Proc. of the First International Conference on Embedded Network Sensor Systems, 2003.

[49] A. Cerpa, N. Busek, and D. Estrin. Scale: "A tool for simple connectivity assessment in lossy environments". Technical Report 0021, Sept. 2003.

[50] Paradis L, Han Q. "A survey of fault management in wireless sensor networks". Journal of Network and Systems *Management* 2007; 15(2), pp.171-190.

[51] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar. "Next century challenges: Scalable coordination in sensor networks". In Proc. of the 5th

Annual International Conference on Mobile Computing and Networking (ACM Mobicom 1999), Aug. 1999.

[52] R. Subramanian and F. Fekri, "Sleep scheduling and lifetime maximization in sensor networks: fundamental limits and optimal solutions," in IPSN '06: Proceedings of the fifth international conference on Information processing in sensor networks. New York, NY, USA: ACM Press, 2006, pp. 218–225.

[53] K.Virk, J. Madsen, A.V. Lorentzen, M. Leopold, P. Bonnet, M. Hansen, "Design of a development platform for HW/SW codesign of wireless integrated sensor nodes", in Proceedings. 8th Euromicro Conference, Sept. 2005, pp. 254 –260.

[54] A. Nisbet and S. Dobson, "A systems architecture for sensor networks based on hardware/software co-design", In Proc. of the 1st IFIP Workshop on Autonomic Communications, Springer Verlag, 2004, pp.115-126.

[55] Y. Li, T. Callahan, E. Darnell, R. Harr, U. Kurkure and J. Stockwood, "Hardware-Software Co-Design of Embedded Reconfigurable Architectures", Proc. of the Design Automation Conference, Los Angeles, California, 2000.

[56] W. Su amd T.L. Lim, "Cross-layer design and optimisation for wireless sensor networks". In Proc. of 7th ACIS International Conference on Sotware Engineering, Artificial Intelligence, Networking and Parallel/Distributed Computing *SNPD'06*, 2006.

[57] R. Kumar, S. PalChaudhuri, D. Johnson and U. Ramachandran, "Network Stack Architecture for future sensors". Rice Technical Report 04-447, [Online] http://www.cs.rice.edu/~santa/research/stack

[58] C. J. Merlin and W. B. Heinzelman, "X-lisa: A cross-layer information-sharing architecture for wireless sensor networks," University of Rochester, Technical Report, Dec. 2006. [Online]. Available: http://www.ece.rochester.edu/~merlin/Xlisa/X-lisa_URTR.pdf

[59] P.J. Marrón, A. Lachenman, D. Minder, J. Hähner, R. Sauter, K. Rothermel "TinyCubus: a flexible and adaptive framework for sensor networks". In Proceedings of the 2nd European Workshop on Wireless Sensor Networks, 2005; pp. 278-289.

[60] A. Tavakoli, P. Dutta, J. Jeong, S. Kim, J. Ortiz, P. Levis, and S. Shenker, "A Modular Sensornet Architecture: Past, Present, and Future Directions". In Proc. of the International Workshop on Wireless Sensornet Architecture (WWSNA), 2007.

[61] (2009) TinyOS open-source operating system for wireless sensor networks. [Online]. Available: http://www.tinyos.net/scoop/

[62] (2009) IEEE 802.15.4 (Zigbee). [Online]. http://ieee802.org/15/pub/TG4.html

[63] (2009) TelosB Platform Cross-Bow. [Online]. Available: http://www.xbow.com/Products/productdetails.aspx?sid=252

[64] K Sohrabi, J. Gao, J, Ailawhadi and G. Pottie, "Protocols for Self-organization of a Wireless Sensor Network". In *IEEE Personnal Communications*, Vol. 7, no5, Oct. 2000.

[65] Note. J. N. AL-Karaki, A. E. Kamal, "Routing Techniques in Wireless Sensor Networks: A Survey", IEEE Wireless Communications, Volume 11, Issue 6, Dec. 2004 pp. 6-28.

[66] C. Intanagonwiwat, R. Govindan, and D. Estrin. "Directed Diffusion: AScalable andRobustCommunicationParadigm for Sensor Networks". In Proceedings of the Sixth annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom), pp. 56-67, Aug. 2000.

[67] C.Intanagonwiwat, R.Govindan, D.Estrin, J.Heidemann, F.Silva,"Directed Diffusion for wireless sensor networking" Networking Volume 11, Issue 1, Feb. 2003, pp. 2-16.

[68] R.C. Shah, J. Rabaey. "Energy Aware Routing for Low Energy Ad Hoc Sensor Networks". In Proc. of IEEE Wireless Communications and Networking Conference (WCNC), Orlando, FL, Mar 2002, pp. 350-355.

[69] B. Zhou, A. Marshall, T.H. Lee, "An Energy-Aware Virtual Backbone Tree for Wireless Sensor Networks", Proceedings of IEEE Globecom 2005, St Louis, USA, Volume 1, 28 Nov.-2 Dec. 2005, pp. 162–167.

[70] Demirkol I, Ersoy C, Alag¨oz F. "MAC Protocols for Wireless Sensor Networks: A Survey". IEEE Communications Magazine 2006; pp. 115–121.

[71] W. Ye, F. Silva, and J. Heidemann, "Ultra-low duty cycle MAC with scheduled channel polling". In In Proc. ACM Conference on Embedded Networked Sensor Systems, SenSys'06, 2006.

[72] I. Rhee, A. Warrier, M. Aia, and J. Min, "Z-MAC: a hybrid MAC for wireless sensor networks". In Proc. ACM Conference on Embedded Networked Sensor Systems, SenSys'05, 2005.

[73] I. Rhee, A.Warrier, J.Min, and L. Xu, "DRAND: Distributed randomized TDMA Scheduling for Wireless Ad Hoc Networks". In Proc. 7th ACM Symp. Mobile Ad Hoc Networking and Computing (MobiHoc'06), New York, 2006, pp. 190–201.

[74] C. Santivanez, J. Redi, "On the use of directional antennas for sensor networks", in: Proc. of IEEE Military Communications Conference (MILCOM 2003), Boston, 2003, pp. 670-675.

[75] T. Dimitriou, A. Kalis, "Efficient Delivery of Information in Sensor Networks using Smart Antennas". In 1st International Workshop on Algorithmic Aspects of Wireless Sensor Networks (ALGOSENSORS 2004), vol. 3121, New York, 2004, pp. 109-122.

[76] J. Cho et al, "Directional Antenna at Sink (DAaS) to Prolong Network Lifetime in Wireless Sensor Networks," in European Wireless, Athens, Apr. 2006.

[77] D. Leang, A. Kalis, "Smart SensorDVBs: Sensor Network Development Boards with Smart Antennas", in: Proc. of IEEE International Conference on Communications, Circuits and Systems (ICCCAS 2004), June 2004, vol. 2, p. 1476-1480.

[78] G. Giorgetti, A. Cidronali, S. K. S. Gupta, G. Manes, "Exploiting Low-Cost Directional Antennas in 2.4 GHz IEEE 802.15.4 Wireless Sensor Networks", Proceedings of the 10th European Conference on Wireless Technology, Oct. 2007, pp.217-220.

[79] (2009) MaxBeam Switched Beam Antenna, Airgain, Inc. [Online]. Available: http://www.airgain.com/A2475.html

[80] Zhao Y, Govindan R, Estrin D. "Residual Energy Scan for Monitoring Sensor Networks". In Proc. of IEEE Wireless Communications and Networking Conference 2002 (WCNC'02), Orlando, USA, Mar. 2002.

[81] Mini R, Loureiro A, Nath B. "The Distinctive Design Characteristic of a Wireless Sensor Network: the Energy Map". *Computer Communications* 2004; 27(10), pp. 935-945.

[82] Zhou N, Wu H, AA. Abouzeid. "Reactive Routing Overhead in Networks with Unreliable Nodes". In Proc. of the Annual International Conference on Mobile Computing and Networking 2003 (MobiCom'03), San Diego, USA, Sept. 2003.

[83] Stojmenovic I, Lin X. "Power Aware Localized Routing in Ad Hoc Networks". IEEE Transactions on Parallel and Distributed Systems 2001; 12(10), pp. 1023-32.

[84] Baek S, Veciana G. "Spatial Energy Balancing through Proactive Multipath Routing in Wireless Multihop Networks". IEEE/ACM Transactions on Networking 2007; 15(1), pp. 93-104.

[85] M. Rossi, M. Zorzi, "Integrated Cost-Based MAC and Routing Techniques for Hop Count Forwarding in Wireless Sensor Networks". In IEEE Transactions on Mobile Computing, Vol.6, No.4, April 2007.

[86] J. Dunlop, F. Kolberg. "Impact of Node Failure for Duty-Cycle MAC Protocol Design in Wireless Sensor Networks". In Proc. of IEEE International Symposium on Wireless Pervasive Computing 2008 (ISWPC'08), Santorini, Greece, May 2008.

[87] F Ingelrest, N Mitton and D Simplot-Ryl, "A Turnover based Adaptive HELLO Protocol for Mobile Ad Hoc and Sensor Networks". MASCOTS'07.

[88] (2009) Tmote. [Online]. Available: http://www.sentilla.com/moteiv-transition.html

[89] C. Park, K. Lahiri, and A. Raghunathan, "Battery Discharge Characteristics of Wireless Sensor Nodes: An Experimental Analysis," Proc. IEEE Comm. Soc. Conf. Sensor and Ad Hoc Comm. and Networks (SECON '05), 2005.

[90] D. Kotz, C. Newport, R. S. Gray, J. Liu, Y. Yuan, and C. Elliott, "Experimental evaluation of wireless simulation assumptions," in Proc. of the

ACM/IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), Oct. 2004, pp. 78–82.

[91] J. Ma et al, "An empirical study of radio signal strength in sensor networks," unpublished. http://www.cs.ust.hk/~majian/

[92] T. S. Rappaport, Wireless Communications, Principles and Practice. Prentice Hall, 1996.

[93] A. Iyer and C. Rosenberg, “What is the Right Model for Wireless Channel Interference?,” in 3rd International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks, QShine, 2006.

[94] D. Son, B. Krishnamachari and J. Heidemann, “Experimental study of concurrent transmission in wireless sensor networks”. In Proc. Second ACM Conference on Embedded Networked Sensor Systems, SenSys'06, 2006.

[95] (2009) OMNeT++. [Online]. http://www.omnetpp.org/

[96] (2009) Network Simulator NS-2. [Online]. http://www.isi.edu/nsnam/ns/

[97] (2009) Mobility Framework. [Online]. http://mobility-fw.sourceforge.net/

[98] C. Mallanda, A. Suri, V. Kunchakarra, S.S. Iyengar, R. Kannan, and A. Durresi. “Simulating Wireless Sensor Networks with Omnet++”. IEEE Computers, 2005.

[99] (2009) Inet Framework. [Online] http://www.omnetpp.org/doc/INET/

[100] (2009)PAWiS Simulation Framework. [Online]. http://pawis.sourceforge.net/

[101] (2009) Merlin Simulation Framework. [Online]. http://www.csi.ucd.ie/students/ARuzzelli/home/MERLIN.html

[102] C. E. Perkins, E. M. Royer, “Multicast operation of the Ad hoc on-demand distance vector routing protocol”, Proceedings of the 5th International Conference on Mobile Computing and Networking (MobiCom 99), August 1999.

[103] (2009) Tmote mini. [Online]. Available: http://www.sentilla.com/pdf/eol/Tmote_Mini_Datasheet.pdf

[104] S. Moon, T. Kim, H. Cha, "Enabling Low Power Listening on IEEE 802.15.4-based Sensor Nodes", The 5th IEEE Wireless Communications & Networking Conference (WCNC 2007), Hong Kong, China, Mar. 2007.

[105] J. Wang, Y. Fang, and D. Wu, “SYN-DMAC: A Directional MAC Protocol for Ad Hoc Networks with Synchronization,” IEEE Milcom 2005, Atlantic City, NJ, USA, Oct. 2005.

[106] B. Hull, K. Jamieson, and H. Balakrishnan, “Mitigating congestion in wireless sensor networks,” in Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems (SenSys '04), pp. 134–147, Baltimore, Md, USA, Nov. 2004.

[107] J. Cortes, Q. Wang, and J. Dunlop, “Novel Metric for Identifying Energy-Vulnerable Nodes and Corresponding Proactive Schemes in Wireless Sensor

Networks", Proc. IEEE Wireless Communications and Networking Conference 2009 (IEEE WCNC'09), Budapest, Hungary, Apr. 2009.

[108] (2009) Mobile Robots of Boston Dynamics. [Online] http://www.bostondynamics.com/content/sec.php?section=BigDog

[109] Chang C, Chang S, Li M, Chen Y. "Energy-efficient mechanisms for coverage recovery in WSNs". In Proc. of IEEE International Wireless Communications and Mobile Computing Conference (IWCMC'08), Crete, Greece, Aug. 2008.

[110] Dressler F, Dietrich I. "Lifetime analysis in heterogeneous sensor networks". In Proc. of IEEE EUROMICRO Conference on Digital System Design: Architectures, Methods and Tools (DSD'06), Dubrovnik, Croatia, Aug 2006.

[111] Akcan H, Kriakov V, Brönnimann H, Delis A. "GPS-free node localization in mobile wireless sensor networks". In Proc. of ACM International Workshop on Data Engineering for Wireless and Mobile Access (MobiDE'06), Chicago, USA, Jun. 2006.

[112] Bhardwaj M, Garnett T, Chandrakasan AP. "Upper bounds on the lifetime of sensor networks". In Proc. of the IEEE International Conference on Communications 2001 (ICC'01), Helsinki, Finland, Jun. 2001.

Appendix A:

Simulation Input and Output

Simulation Input Parameters

```
[General]
network = sim
```

Simulation time, OMNeT++ Simulator parameters and Output Vectors for Statistics Results

```
sim-time-limit = 2000s           [Tkenv]                          [Cmdenv]
                                 bitmap-path="./../bitmaps"       #for non-express mode
#Random Seeds                    default-run=1                    express-mode = no
num-rngs = 3                     use-mainwindow = yes             module-messages = no
seed-0-mt = 340176714            print-banners = no               event-banners = no
seed-1-mt = 1090896140           slowexec-delay = 300ms           status-frequency = 5000
seed-2-mt = 1276750079           update-freq-fast = 10            performance display = no
sim.host[*].nic.mac.rng-0 = 0    update-freq-express = 100        runs-to-execute = 1
sim.host[*].nic.mac.rng-1 = 1    breakpoints-enabled = yes
sim.host[*].nic.mac.rng-2 = 2    event-banners = no

[OutVectors]                                            #         Vectors
**.LevelCount.enabled = no                               #Battery
**.Sink_Delay.enabled=no                                 #Delay Pkts at Sink
**.Rcvd_Pkts.enabled=no                                  #Rcvd Pkts for every node
**.Contention_Index.enabled=no                           #Contention Index of every node
**.Number of Sending Neighbours.enabled=no               #Number of Senders
**.Extra NAVs Added Duration.enabled=no                  #Extra of NAV scheduling
**.Extra Backoffs Added CW.enabled=no                    #Extra Bacoffs CW used
**.Battery_Index.enabled=no                              #Evolution of Battery Index
**.sinkFwdPkts.enabled=yes                               #Rcvd Pkts at the Sink
```

Network area, number of nodes, topology generator (-1=Random) and sink IDs

```
#Network Size                      #Sinks
sim.playgroundSizeX = 500          sim.host[*].nic.mac.sinkId= 0
sim.playgroundSizeY = 500          sim.host[*].nic.mac.sinkId2= 0
sim.numHosts = 100                 sim.host[*].nic.mac.sinkId3= 0
                                   sim.host[*].nic.mac.sinkId4= 0
#Topology Generator                sim.host[*].nic.mac.sinkId5= 0
sim.host[*].mobility.dist=50
sim.host[*].mobility.nRGrid=1
sim.host[*].mobility.x=-1
sim.host[*].mobility.y=-1
```

Position of sinks and mobile nodes parameters

```
#Position of Sinks
sim.host[0].mobility.x=250
sim.host[0].mobility.y=250

#Mobile nodes
"MassMobility" "ConstSpeedMobility" "LinearMobility" "RectangleMobility"
"CircleMobility
sim.host[100].nic.mac.ImRobot = true
sim.host[100].mobilityType = "CircleMobility"
```

ChannelControl Parameters (how far (range) the additive interference is considered)

```
sim.channelcontrol.carrierFrequency = 2400E+6
sim.channelcontrol.pMax  = 1     # max transmission power [mW]
sim.channelcontrol.sat   = -106  # signal attenuation threshold [dBm]
sim.channelcontrol.alpha = 2.8   # path loss coefficient alpha
```

Parameters for the Application Layer

```
sim.host[*].appl.headerLength=256
sim.host[*].appl.burstSize=1
sim.host[*].appl.twoWayHandshake = false
sim.host[*].appl.interArrivalTime = 20
sim.host[*].appl.frameDuration = 10
sim.host[*].appl.generatePeriodicData = true
sim.host[*].appl.numSources = 300
sim.host[*].appl.startTime = 9.99
```

```
sim.host[*].appl.generatePoissonData = false
sim.host[*].appl.generateBurstyData = false ;
sim.host[*].appl.burstLength = 5
sim.host[*].appl.delay_app_init = 0.0
sim.host[*].appl.init_frame_time = 9.99
sim.host[*].appl.percentage_source = 1.0
# percentage of nodes that tx data
```

Parameters for the MAC Layer: SSAS and Proactive Schemes

```
    #### SSAS ####
sim.host[*].nic.mac.SSAS = true
sim.host[*].nic.mac.SSAS_M = false
sim.host[*].nic.mac.FWDuration = 0.1 #sec
sim.host[*].nic.mac.CSMAFwding = false
sim.host[*].nic.mac.doingAggreg = true
sim.host[*].nic.mac.timeOutTMAC = 0.015 #sec
sim.host[*].nic.mac.reductionActTime0Hop2Sink = 0.00
sim.host[*].nic.mac.advanceSleep = true      #Adaptive Sleeping
sim.host[*].nic.mac.adaptiveSlot = true      #Adaptive Slot
sim.host[*].nic.mac.adaptiveTxPower = false
sim.host[*].nic.mac.trainingFrames = 10      #Training period for Adaptive Schemes
sim.host[*].nic.mac.reTxonRequest = false
sim.host[*].nic.mac.ADV_b4FWD = false
sim.host[*].nic.mac.upadateNeighbours = true

      ### Proactive Schemes for Vulnerable Nodes ####
sim.host[*].nic.mac.rescueRobot = false
sim.host[*].nic.mac.extendTDMA = false
sim.host[*].nic.mac.trafficBalancing = true
sim.host[*].nic.mac.dynamicRouting = false
```

```
sim.host[*].nic.mac.vulnerabilityActionTime = 210  #seconds  #VCTs
sim.host[*].nic.mac.vulUpdateTime = 150   #seconds

                #### Failure Options ####
sim.host[*].nic.mac.time_of_Death = 5000
sim.host[*].nic.mac.nodeDeath = false
sim.host[node].nic.mac.nodeDeath = true #= true means node will die at time_of_Death

        #### General MAC operation parametres####
sim.host[*].nic.mac.twoWayHandshake = false
sim.host[*].nic.mac.shortRTSHandshake = false
sim.host[*].nic.mac.meanArrivalTimeTC = 0.2 # unit of time = frameDuration ->
lambda=frameDuration/meanArrivalTimeTC
sim.host[*].nic.mac.generateTC = false
sim.host[*].nic.mac.fixedRouting = true
sim.host[*].nic.mac.routingType = 0 # should always be 0
sim.host[*].nic.mac.queueingType = 0 # should always be 0
sim.host[*].nic.mac.ownQueueLength=20
sim.host[*].nic.mac.fwdQueueLength=80
sim.host[*].nic.mac.priorityOwnQueue= true
sim.host[*].nic.mac.timeoutCounterValue = 12
sim.host[*].nic.mac.headerLength= 24
sim.host[*].nic.mac.busyRSSI=-94; [dB] # CCA_Rssi, CC2420 Sensitivity
sim.host[*].nic.mac.slotDuration=0.0002
sim.host[*].nic.mac.difs=0.00035
sim.host[*].nic.mac.maxTxAttempts=12 # 7
sim.host[*].nic.mac.defaultChannel = 0
sim.host[*].nic.mac.bitrate = 250E+3      #250kbps
sim.host[*].nic.mac.contentionWindow = 25
sim.host[*].nic.mac.maxAuthDelay = 50.0
sim.host[*].nic.mac.minThroughput = 0.55

sim.host[*].nic.mac.frameDuration= 10
sim.host[*].nic.mac.dutyCycle = 1.0
sim.host[*].BatteryModule.dutyCycle = 1.0 ;
sim.host[*].nic.mac.delta= 0.0002
sim.host[*].nic.mac.contentionIndexThreshold = 0.0
sim.host[*].nic.mac.navAdapt = false ;
sim.host[*].nic.mac.backoffAdapt = false ;
sim.host[*].nic.mac.factorCW = 1 ; unsigned int;
sim.host[*].nic.mac.factorExtraNAV = 1.0 ;
sim.host[*].nic.mac.txAttemptsAdapt = true ;
```

Parameters for the Physical Layer

```
#Transceiver
sim.host[*].nic.snrEval.publishRSSIAlways = 1
sim.host[*].nic.snrEval.headerLength=16
sim.host[*].nic.radio.turnOn = 0.004
sim.host[*].nic.radio.swSleep =0.0001
sim.host[*].nic.radio.swIdle = 0.0001
sim.host[*].nic.radio.swSend = 0.0001
```

```
sim.host[*].nic.radio.swRecv = 0.0001
# transmission power [mW]  0 / -1  /  -3 / -5  / -7  /  -10 / -15 / -25
#"1 / 0.7943 / 0.5 / 0.3162 / 0.1995 / 0.1 0.03162 / 0.003162"
sim.host[*].nic.snrEval.transmitterPower= 1
sim.host[*].nic.snrEval.carrierFrequency=2400E+6

#Channel Model (snreval)
sim.host[*].nic.snrEval.thermalNoise=-107
sim.host[*].nic.snrEval.sensitivity=-94
sim.host[*].nic.snrEval.pathLossAlpha=2.8

# Interference Model (decider)
sim.host[*].nic.decider.snrThresholdLevel=5;[dB]
sim.host[*].nic.decider.snirThreshold=5; in dB
sim.host[*].nic.decider.bitRate = 250E+3; 250kbps

#Parameters for the Smart Antenna
sim.host[*].nic.snrEval.BWFN = 30;  #When Sectors = 0 (dynamic array)
sim.host[*].nic.snrEval.Gmb = 9.3;[dB]
sim.host[*].nic.snrEval.MSLL = -12;[dB]
sim.host[*].nic.snrEval.MainLobe_Percentage = 0.7;[%]
# Adaptive Antenna Array (Sectors=0)
# Omnidirectional Only (Sectors=1)
# or Switched Beam Antennas (Sectors>1)
#Number of Sectors of the SBA
sim.host[*].nic.snrEval.Sectors = 1
sim.host[*].nic.mac.Sectors = 1
#Directional NAV Capability
sim.host[*].nic.mac.DoingDNAV = false

#Parameters for the Battery Module
sim.host[*].BatteryModule.batteryCapacity = 3000 ;mA/sec
sim.host[*].BatteryModule.batteryTX = 19.5 #mA 19.5 18.4 16.9 15.4 14.08 12.1 10.89 9.68
sim.host[*].BatteryModule.batteryRECV = 21.8 ; 21.8mA
sim.host[*].BatteryModule.batterySLEEP = 0.02 ; 20uA
sim.host[*].BatteryModule.batteryIDLE = 0.5 ; 0.5mA
sim.host[*].BatteryModule.updateTimer = 1
```

Simulation Output Performance Metrics

General Simulation Statistics

number nodes	100
SBA sectors	5
frame duration	10
duty cycle	2,15
distance	50
simulTime	500
Inter-arrival Appl packet	20
Total number of pkts sent to sink	2425,5
Initial battery	3000
Max Auth delay	200
fixed routing	1
Queue length	100
Perc of sensors that have Tx	100
Max thruput achieved by a sensor	102,040816
Min thruput achieved by a sensor	20,4081633
Perc packets over delay	0,0556793
Perc. Pkts acquired at sink	**74,0465883**
Mean delay to sink	**7,6391**
Mean Perc battery used	**2,91057172**
Mean Battery level	2912,68263
Battery at Sink	19774
Collision at Sink	1174
Mean number collision pkts	198,717172
Mean number interf pkts	26,5959596
Mean number dropped pkts	0
Mean number dropped fwd pkts	0
Mean number timeout ctrl pkts	3,16161616
Mean number re-Tx per data pkt Tx to sink	4,02927231
Number pkts DUP rcvd at sink	124
Jain's Fairness Index at sink	0,86419765
Max number hops to sink	4
Mean number hops to sink	2,21212121
Time TX	0,19183463
Time RX	2,72566184
Time SLEEP	488,463374
Time IDLE	1,08293184
Time SWITCHING	6,53618992
Deviation Battery	0,61361258
Perc Nodes Dead	0
Drop FWD delay	0
Mobile Nodes, %Pkts Sent OK, Drop Pkets, Bat Used	

Overall Simulation Metrics at the SINK

```
Calling finish() at end of Run #1...
Application Packets sent = 10 //Packets generated at each node
Inter-arrival time = 20
route for node = 0, mac address = 108

//SINK
sensor = 0, Number of neighbours = 0

sensor = 0, IDs of neighbours =
Number of packets transmitted to sensor 0:
```

```
sensor = 0, received from2sink 1, = 8
sensor = 0, received from2sink 2, = 7
sensor = 0, received from2sink 3, = 10
sensor = 0, received from2sink 4, = 10
sensor = 0, received from2sink 5, = 10
sensor = 0, received from2sink 6, = 10
sensor = 0, received from2sink 7, = 10
sensor = 0, received from2sink 8, = 8
sensor = 0, received from2sink 9, = 10
sensor = 0, received from2sink 10, = 10
sensor = 0, received from2sink 11, = 7
sensor = 0, received from2sink 12, = 10
sensor = 0, received from2sink 13, = 10
sensor = 0, received from2sink 14, = 10
sensor = 0, received from2sink 15, = 9
sensor = 0, received from2sink 16, = 10
sensor = 0, received from2sink 17, = 2
sensor = 0, received from2sink 18, = 10
sensor = 0, received from2sink 19, = 9
sensor = 0, received from2sink 20, = 8
sensor = 0, received from2sink 21, = 9
sensor = 0, received from2sink 22, = 10
sensor = 0, received from2sink 23, = 5
sensor = 0, received from2sink 24, = 5
sensor = 0, received from2sink 25, = 10
sensor = 0, received from2sink 26, = 7
sensor = 0, received from2sink 27, = 9
sensor = 0, received from2sink 28, = 9
sensor = 0, received from2sink 29, = 9
sensor = 0, received from2sink 30, = 9
sensor = 0, received from2sink 31, = 8
sensor = 0, received from2sink 32, = 10
sensor = 0, received from2sink 33, = 10
sensor = 0, received from2sink 34, = 10
sensor = 0, received from2sink 35, = 10
sensor = 0, received from2sink 36, = 10
sensor = 0, received from2sink 37, = 9
sensor = 0, received from2sink 38, = 8
sensor = 0, received from2sink 39, = 10
sensor = 0, received from2sink 40, = 8
sensor = 0, received from2sink 41, = 9
sensor = 0, received from2sink 42, = 8
sensor = 0, received from2sink 43, = 10
sensor = 0, received from2sink 44, = 9
```

```
sensor = 0, received from2sink 51, = 9
sensor = 0, received from2sink 52, = 10
sensor = 0, received from2sink 53, = 10
sensor = 0, received from2sink 54, = 9
sensor = 0, received from2sink 55, = 10
sensor = 0, received from2sink 56, = 8
sensor = 0, received from2sink 57, = 8
sensor = 0, received from2sink 58, = 6
sensor = 0, received from2sink 59, = 8
sensor = 0, received from2sink 60, = 7
sensor = 0, received from2sink 61, = 9
sensor = 0, received from2sink 62, = 4
sensor = 0, received from2sink 63, = 7
sensor = 0, received from2sink 64, = 10
sensor = 0, received from2sink 65, = 10
sensor = 0, received from2sink 66, = 10
sensor = 0, received from2sink 67, = 10
sensor = 0, received from2sink 68, = 10
sensor = 0, received from2sink 69, = 10
sensor = 0, received from2sink 70, = 8
sensor = 0, received from2sink 71, = 9
sensor = 0, received from2sink 72, = 9
sensor = 0, received from2sink 73, = 9
sensor = 0, received from2sink 74, = 7
sensor = 0, received from2sink 75, = 8
sensor = 0, received from2sink 76, = 7
sensor = 0, received from2sink 77, = 9
sensor = 0, received from2sink 78, = 10
sensor = 0, received from2sink 79, = 10
sensor = 0, received from2sink 80, = 10
sensor = 0, received from2sink 81, = 10
sensor = 0, received from2sink 82, = 10
sensor = 0, received from2sink 83, = 4
sensor = 0, received from2sink 84, = 9
sensor = 0, received from2sink 85, = 4
sensor = 0, received from2sink 86, = 9
sensor = 0, received from2sink 87, = 10
sensor = 0, received from2sink 88, = 6
sensor = 0, received from2sink 89, = 10
sensor = 0, received from2sink 90, = 9
sensor = 0, received from2sink 91, = 9
sensor = 0, received from2sink 92, = 10
sensor = 0, received from2sink 93, = 9
sensor = 0, received from2sink 94, = 9
```

```
sensor = 0, received from2sink 45, = 10     sensor = 0, received from2sink 95, = 6
sensor = 0, received from2sink 46, = 7      sensor = 0, received from2sink 96, = 7
sensor = 0, received from2sink 47, = 10     sensor = 0, received from2sink 97, = 10
sensor = 0, received from2sink 48, = 9      sensor = 0, received from2sink 98, = 10
sensor = 0, received from2sink 49, = 9      sensor = 0, received from2sink 99, = 10
sensor = 0, received from2sink 50, = 10
```

```
Number of DUPLICATE packets transmitted to sensor = 0, = 12
sensor = 0, I am alive = 1
sensor = 0, battery left sink = 9865.15
number of sensors that have Tx successfully to Sink = 99
Mean number of Tx per sensor = 8.74747
Max number of Tx by a sensor = 10
Min number of Tx by a sensor = 2
Median number of Tx per sensor = 6
Percentage of packets that arrived after the delay bound = 0
smoothingFactor = 0.3
energy level threshold = 0.2
generate TC = 0
meanArrivalTimeTC = 0.2
warming up period = 100000
fixed routing = 1
ownQueueLength = 20
fwdQueueLength = 100
priorityOwnQueue = 1
timeoutCounterValue = 12
maxContentionWindow = 25
minContentionWindow = 13
frame duration = 10
dutyCycle = 1
end-to-end delay limit = 100
minimum Throughput expected = 0.55
number of received packets by the sink = 1732
mean delay to the sink = 8.69524
number of timeouts CTRL at sink = 0
number of timeouts DATA at sink = 0
number of collision pkts at sink = 12
sectors = 1
------------------------------------------------------------
TC packets stats: //Alarms (TC= Time Critical)
mean delay to the sink for TC = -1.#IND
sensor = 0, TC ack sent = 0
host = 0, number of TC sent = 0
sensor = 0, number of TC received = 0
sensor = 0, number of TC dropped = 0
sensor = 0, number of old TC Pkts (deleted) = 0
sensor = 0, old Fwd TC Pkts (deleted) = 0
sensor = 0, number of TC DUPLICATED data transmitted to sensor = 0
sensor = 0, number of Rcvd TC pkts to send = 0
sensor = 0, number of delay too long TC = 0
sensor = 0, number of drop FWD TC pkts = 0
number pkts in macQueueTC = 0, in fwdTC queue = 0
sensor = 0, number of ACK TC pkts Rcvd (for own pkts) = 0
------------------------------------------------------------
sensor = 0, NAV: 0; 0
sensor = 0, number of sending neighours = 99, at the end of this simulation
sensor = 0, number of extra NAVs: 0
```

```
sensor = 0, number of extra backoffs: 0

//Summary of parameters
ID      MACAdrr        rcvd    ack      interfer  collision      Error   Drop    DropFwd
        navTime        avgPkLife        TOuts     TOData         BatLeft numHopstoSink
timeDeath      TimeTX          TimeRX             TimeSLEEP      TimeIDLE
TimeSWITCH
0       108     1732   0       0        12        0       0      0       0       8.69524 0
        0       9865.15 9999
Times = 0, 99999,
Times2 = 0, 29.8, 99999, 9999, 250.0, 250.0, 0.005760, 6.041260, 202.935380, 0.000000, 0.017600;
dutyCycle in Battery Module = 1
```

Paritcular Simulation Metrics: Any Node (e.g. Sensor Node 1)

```
Application Packets sent = 11
Inter-arrival time = 20
route for node = 1, mac address = 119
sensor = 1, Number of neighbours = 4
//Senders
host[1]::SMACMacLayer: rssi 216.265 nexthop 1120 number of hops 4 active 1
sensor = 1, ID of neighbour = 92
host[1]::SMACMacLayer: rssi 531.835 nexthop 548 number of hops 5 active 1
sensor = 1, ID of neighbour = 40
host[1]::SMACMacLayer: rssi 289.223 nexthop 636 number of hops 5 active 1
sensor = 1, ID of neighbour = 48
host[1]::SMACMacLayer: rssi 152.715 nexthop 900 number of hops 5 active 1
sensor = 1, ID of neighbour = 72

sensor = 1, IDs of neighbours = 92, 40, 48, 72,
Number of packets transmitted to sensor 1:
Number of DUPLICATE packets transmitted to sensor = 1, = 0
sensor = 1, I am alive = 1
sensor = 1, number of TC dropped = 0
sensor = 1, num_hops to sink = 4
sensor = 1, num frames = 20
sensor = 1, num frames in which Tx Own Packets = 8
sensor = 1, num frames in which Tx Fwd Packets = 0
sensor = 1, mean number of own packets sent per frame when Tx = 1.25
sensor = 1, mean number of packet fwd per frame when Tx = -1.#IND
sensor = 1, min number of packets sent per frame when Tx = 1
sensor = 1, max number of packets sent per frame when Tx = 2
sensor = 1, min number of packets fwd per frame when Tx = -1
sensor = 1, max number of packets fwd per frame when Tx = -1
sensor = 1, number of interference packets received = 4
sensor = 1, number of collision packets received = 8
sensor = 1, number of error packets received = 0
sensor = 1, number of dropped packets = 0
sensor = 1, number of dropped FWD packets = 0
sensor = 1, number of timeouts = 20
sensor = 1, number of data timeouts = 0
number pkts in macQueue = 1, in fwd queue = 0
sensor = 1, contention index = 0.750000
sensor = 1, number of RTS packets sent out = 32
sensor = 1, number of expected CTS packets received = 8
```

```
sensor = 1, number of total CTS packets received = 10
sensor = 1, number of total RTS packets received = 68
sensor = 1, battery left = 278.431860
sensor = 1, batteryleft = 278.432
sensor = 1, perc. left = 92.8106
***************************************************************
sensor = 1, BATTERY INDEX = 3.31468
***************************************************************
sensor = 1, dead time = 99999.000000
sensor = 1, ownThroughput = 0.909091
sensor = 1, received packets from sending neighbours = 0
sensor = 1, ackRcvd = 10
sensor = 1, numPktsRcvdToSend = 11
sensor = 1, number of TimeoutCounter occurences = 0
sensor = 1, number of packets outside the maxAuthDelay deleted from Queue = 0
sensor = 1, number of Fwd packets outside the maxAuthDelay deleted from Queue = 0
sensor = 1, initial battery = 300
Delay from sensor 1:
sensor = 1, mean end-to-end delay = -1.#IND
Energy left in next hop 1:
next hop = 1120, energy left (perc. of initial energy) = 0
next hop = 548, energy left (perc. of initial energy) = 0
next hop = 636, energy left (perc. of initial energy) = 0
next hop = 900, energy left (perc. of initial energy) = 0
------------------------------------------------------------
TC packets stats:
sensor = 1, TC ack sent = 0
host = 1, number of TC sent = 0
sensor = 1, number of TC received = 0
sensor = 1, number of TC dropped = 0
sensor = 1, number of old TC Pkts (deleted) = 0
sensor = 1, old Fwd TC Pkts (deleted) = 0
sensor = 1, number of TC DUPLICATED data transmitted to sensor = 0
sensor = 1, number of Rcvd TC pkts to send = 0
sensor = 1, number of delay too long TC = 0
sensor = 1, number of drop FWD TC pkts = 0
number pkts in macQueueTC = 0, in fwdTC queue = 0
sensor = 1, number of ACK TC pkts Rcvd (for own pkts) = 0
------------------------------------------------------------
sensor = 1, NAV: 0.23656; 69
sensor = 1, number of sending neighours = 0, at the end of this simulation
sensor = 1, number of extra NAVs: 0
sensor = 1, number of extra backoffs: 0
1       119     0       10      4       8       0       0       0       0.23656 0       20
        0       278.432 4
Times = 1, 99999,
Times2 = 1, 3.3, 99999, 4, 85.9 , 65.1 , 0.018944, 0.670375, 207.959158, 0.218384, 0.133140;
dutyCycle in Battery Module = 1
Application Packets sent = 11
Inter-arrival time = 20
route for node = 2, mac address = 130
```

Appendix B:

Papers Published from this Work

The following publications have emerged during the course of the study that is presented in this thesis.

- J. Dunlop and **J. Cortes**, "Impact of Directional Antennas in Wireless Sensor Networks", Proc. IEEE Internatonal Conference on Mobile Adhoc and Sensor Systems, Mass-MeshTech, Pisa, Italy, Oct 2007.
- **J. Cortes** and J. Dunlop, "Co-Design of Efficient Contention MAC with Directional Antennas in Wireless Sensor Networks", Proc. IEEE International Wireless Communications and Mobile Computing Conference, IWCMC, Crete Island, Greece, Aug 2008.
- **J. Cortes**, J. Dunlop and F. Kolberg. "Adaptive MAC with Scheduled Sectorial Access at Sinks (SSAS) in Wireless Sensor Networks", Proc. IEEE International Symposium on Wireless Communication Systems 2008 (ISWCS'08), Reykjavik, Iceland, Oct 2008.
- **J. Cortes**, J. Dunlop and F. Kolberg. "Cross-Layer Design of Adaptive MACs in Wireless Sensor Networks", in the Virginia Tech Symposium on Wireless Personal Communications, Blacksburg, US, Jun 2008.
- **J. Cortes**, Q. Wang, and J. Dunlop, "Novel Metric for Identifying Energy-Vulnerable Nodes and Corresponding Proactive Schemes in Wireless Sensor Networks", Proc. IEEE Wireless Communications and Networking Conference 2009 (IEEE WCNC'09), Budapest, Hungary, Apr 2009.
- **J. Cortes**, Q. Wang, and J. Dunlop, "Cross-Layer Proactive Hybrid MAC to Prolong Lifetime of Wireless Sensor Networks", Proc. the 69th IEEE Vehicular Technology Conference (IEEE VTC2009-Spring), Barcelona, Spain, Apr 2009.