Medium Access Control for Wireless Sensor Networks with Directional Antennas

Doctor of Philosophy Ph.D.

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Abstract

This thesis explores Medium Access Control (MAC) protocol design for wireless sensor networks (WSNs) with directional antennas. In particular, this work focuses on ways of realistically improving the network performance and quality of service (QoS) with directional antennas. MAC protocols play a vital role in making effective use of a multi-access channel as they govern the achievable channel utilisation efficiency and QoS. Conventional MAC protocols incorporating different multiple channel access techniques were designed for wireless sensor nodes equipped with omni-directional antennas. In order to exploit the potential benefits of directional antennas, modifications and novel designs are required to provide the enhanced performance.

Significant advances in the effectiveness of directional MAC (DMAC) protocols are described, with the enhancements to the channel utilisation shown. These DMAC protocols are able to offer good throughput performance but only with a number of simplifying assumptions and they are limited by the directional antenna pattern. The performance of the DMAC protocols proposed in this thesis are mathematically analysed and evaluated via simulation models with different scenarios. These involve WSNs with various number of sensor nodes, and in some cases with mobile sensor nodes with different speeds, all sharing a single frequency channel.

While in most instances, DMAC protocols assume idealised directional antenna patterns, this thesis presents a novel directional hub MAC protocol that employs realistic directional antennas and power control strategy in order to deliver significantly enhanced performance. An analytical technique is introduced to evaluate the performance of DMAC protocols incorporating a hub node with multiple directional antennas, which is used in combination with simulation to investigate the effects of antenna pattern overlap. While the results show that directional antennas with a suitable MAC protocol can provide enhanced performance, the antenna overlap ratio has a significant impact on the potential improvements. Furthermore, a hybrid DMAC protocol is proposed. It combines realistic directional antennas and adapted multiple channel access techniques in order to significantly improve the performance and QoS, and thus, increase their adaptability in channelling WSN environments.

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Publications

A. Chau, J. F. Dawson, P. D. Mitchell, T. H. Loh, “*Medium access control protocol for wireless sensor networks in Harsh environments with directional antennas*”, The 2018 Loughborough Antennas & Propagation Conference (LAPC 2018), Loughborough, United Kingdom; pp. 1-5.

A. Chau, J. F. Dawson, P. D. Mitchell. “*Medium Access and Power Control Protocol for Wireless Sensor Networks with Directional Antennas*”, The 10th International Conference on Information and Communication Technology Convergence (ICTC 2019), Jeju Island, Korea; pp. 582-586.

A. Chau, J. F. Dawson, P. D. Mitchell, T. H. Loh, "*Virtual Sensing Directional Hub MAC (VSDH-MAC) Protocol with Power Control*", MDPI Electronics, vol. 9, pp. 1219-1236, 2020.

A. Chau, J. F. Dawson, P. D. Mitchell. “*Directional Hub Slotted Aloha Medium Access and Power Control Protocol for Wireless Sensor Networks with Directional Antennas*”, The 55th Annual Conference on Information Sciences and Systems (CISS 2021), Baltimore, USA; pp. 1-5.

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Declaration

This thesis was written by myself and represents my original work, with supervision from Dr John. F. Dawson and Dr Paul. D. Mitchell at the University of York, and collaboration from Prof Tian Hong Loh from the National Physical Laboratory. This thesis has not been submitted for any other award at this or any other institution. The work presented in this thesis has been presented or published as follows:

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A. Chau, J. F. Dawson, P. D. Mitchell, T. H. Loh, "*Medium access control protocol for wireless sensor networks in Harsh environments with directional antennas*", The 2018 Loughborough Antennas & Propagation Conference (LAPC 2018), Loughborough, United Kingdom; pp. 1-5.

Poster Presentations:

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Chapter 1 Introduction

Contents

1.1 Overview

The demand for wireless sensor networks (WSNs) has increased rapidly in recent years. Medium access control (MAC) protocols have become a popular area of research to exploit the potential of WSNs. The main purpose of a WSN is to allow a group of wireless sensor devices to record and monitor data and transmit it back to a base station or a sink. Different applications of WSNs have emerged over the years such as wildlife monitoring [1, 2], safety monitoring [3, 4], healthcare applications [5], vehicle tracking [6, 7] and smart homes/cities [8-10]. Furthermore, popularity of future wireless network monitoring applications in recent years has driven research and development of more energy efficient WSN systems. According to some estimations [11], the global information communication technologies consume around 1800 TW/hr annually. The majority of the wireless sensor nodes operate on batteries with a limited lifetime. The expected lifetime of batteries is around 2 to 3 years, which manifests as in 25000 tons of disposable batteries per year, causing extensive environment and financial concerns [12].

The medium access control (MAC) layer is a part of the data link layer which plays one of the most crucial roles in the communication protocol's overall energy efficiency [13]. MAC protocols are designed to control the access of sensor nodes to a shared medium. In the design of a MAC protocol, one must assume that packets which have collided must be discarded and have to be retransmitted. Due to the limitation on energy and computation resources, MAC protocols are required to provide energy efficient operation in order to maintain a long operating lifetime of the sensor nodes. They must also provide reliable performance by reducing the probability of packet collision.

The advantage of random access protocols (contention free protocols) compared to scheduled access protocols is their simplicity, low energy consumption and latency; however, they do provide a poor link performance (throughput) due to the collisions resulting from their non-synchronised transmission technique. A directional antenna has the potential, compared to an omni-directional antenna, to increase the signal-to-interference-plus-noise ratio (SINR) and spatial reuse between the nodes, thus providing more reliable communication paths. Recently, directional antennas have been applied to WSNs to improve the throughput by exploiting the potential of spatial reuse. The improved performance from the application of directional antennas is however restricted by the antenna pattern [14-18]. This thesis evaluates the performance of MAC protocols with directional antennas. There is also a need to improve the energy efficiency and fairness of the network as well as throughput with directional antennas.

1.2 Scope and Contributions

The main scope of this thesis is to examine contention-based random access MAC protocols for single hop WSNs, focusing on the design and development of MAC protocols suited to handling WSNs incorporating directional antennas. The first goal of the research is to develop a deep and thorough understanding of different techniques and issues associated with MAC protocol design for WSNs, achieved through a comprehensive literature review. The work follows primarily from the Pure Aloha protocol, which is specifically designed to provide low end-to-end delay and energy consumption.

The purpose of this thesis is to examine in detail the performance of directional contention-based random access schemes, whilst taking ideas from other schemes, in order to generate new and improved directional MAC protocols.

A limitation and assumption of previous work presented in the field is the use of an idealised directional antenna pattern, which has been shown to have the possibility to represent throughput performance inaccurately [16, 17]. The primary reason for their continued use in directional MAC protocol design is because they provide simplicity in protocol development as well as mathematical analysis. One of the major contributions of this thesis is an original analysis of the effect of real antenna patterns on network performance, which provides a more realistic network throughput estimation.

Several novel techniques and methods have been developed in this thesis to enhance throughput, achieve better energy efficiency and improve fairness through the application of directional antennas and power management. The novel contributions are presented in the following:

1.2.1 Impact of antenna pattern overlap on link performance

The first main contribution of the work is presented in Chapter 5, to address the antenna pattern issue highlighted in Chapter 3. A modified Pure Aloha scheme is proposed in order to adapt the directional antennas equipped at the hub. A directional hub Aloha (DH-Aloha) MAC protocol is presented and evaluated by analytical and simulation models to measure and validate its performance. The simulation results show the multi-antenna hub approach improves the throughput performance compared to the traditional omni-directional antenna system. Here, a directional antenna is referred as an antenna having the property of radiating or receiving electromagnetic waves more effectively in some specific directions than others [19]. However, the simulations demonstrate that the shape and gain of the main beam, side and back lobes of the directional antenna pattern has a significant influence on the potential throughout improvement.

1.2.2 Transmission power control and fairness enhancement

The second main contribution in Chapter 6 applies a power control strategy in assisting the DH-Aloha protocol to provide an energy efficient and fair network. DH-Aloha is extended to identify the energy consumption and fairness performance and to provide a solution in order to rectify the exiting problems with many MAC designs. A dynamic sensor node transmit power control scheme is proposed and evaluated by analytical and simulation models. The power control strategy has reduced the average transmission power consumption by a factor of 2, and fairness performance has been improved significantly.

1.2.3 A virtual sensing random access and power control protocol

Chapter 7 proposes a contention-based random access approach that provides virtual carrier sensing for WSNs in dynamic environments. A virtual sensing directional hub MAC (VSDH-MAC) protocol and a variant with short physical sensing VSDH-MAC (DIFS-VSDH-MAC) protocol are proposed to provide excellent throughput performance, while limiting energy consumption and sensor node complexity. The simulation results from the proposed protocols were obtained and compared against existing directional MAC protocols.

1.3 Thesis Outline

In Chapter 2, an overview of WSNs is presented, focusing on aspects relating to the design of effective MAC protocols. An overview of a selection of WSN applications is given, along with an insight into the MAC protocol design parameters that need to be considered.

Chapter 3 provides a detailed background literature review on medium access control. A brief overview of the fundamental multiple access techniques is given, along with a selection of energy efficient techniques. The desirable features of a well-designed directional MAC protocol are described and the constraints that directional antennas place on MAC protocol design are identified. The final part of the chapter consists of a comprehensive literature review on the most pertinent directional MAC protocols.

Chapter 4 describes the simulation models that were used in Riverbed Modeler. These models include the link model, propagation model, and the traffic model. The metrics and antenna models used to assess the network performance are also presented.

Chapter 5 first investigates the performance of MAC protocols utilising random access in the form of the Aloha protocols. The theoretical throughput characteristics and stability issues of random access are examined through mathematical analysis. The effects of network node density on throughput performance are evaluated through a combination of simulation and mathematical analysis. These results provide a deeper understanding of the more complex protocols introduced in later chapters. A directional MAC protocol has been modified from the traditional Pure Aloha protocol, known as the Directional Hub Aloha (DH-Aloha). An analytical model for estimating throughput performance of directional MAC protocols is also presented in order to provide a realistic estimation with real antenna patterns. The last section of Chapter 5 presents the simulation results and comparison of the DH-Aloha protocol with varying antenna patterns. The results presented in this chapter provide an understanding of the fundamental behaviour of the contention-based random access directional MAC protocol that was described in Chapter 3. These results also provide useful insights into the effects of directional antennas.

Chapter 6 extends the previous work to investigate the effectiveness of combining directional antennas and random access techniques. The approach enables a higher channel utilisation compared to a single antenna system. A power controlled variant of the DH-Aloha protocol (DH-Aloha-PC) is proposed, which improves sensor node energy efficiency, lifetime, and network fairness.

Chapter 7 proposes the virtual carrier sensing directional hub MAC (VSDH-MAC) protocols, which incorporates an original approach for implementing a carrier sensing random access technique. A pure virtual carrier sensing variant is described, and its performance is evaluated and compared with other directional MAC protocols through simulation in Riverbed Modeler. A variant with additional short physical carrier sensing (DIFS-VSDH-MAC) is also introduced. The merit of the additional sensing is to enhance the throughput performance with a trade-off of slightly higher energy consumption.

Chapter 8 discusses a number of recommendations for further work.

Chapter 9 presents the conclusions of this thesis and summarises its original contributions.

Chapter 2 Wireless Sensor Networks

Content

2.1 Introduction

The use of wireless sensor networks (WSNs) for data harvesting or environmental monitoring has been a great interest of the research community, driven by a wealth of theoretical and practical challenges. The growing interest can be largely attributed to the applications enabled by large-scale networks of small devices capable of harvesting information from the physical environment, performing simple processing tasks and transmitting data to remote locations. These studies have stimulated the development of new WSN services and ushered a surge of WSN applications [20]. Most WSNs measure scalar physical phenomena such as temperature, humidity, pressure, location, or vibration etc [21]. Since these WSNs have started to be part of our life, there are gradually more and more WSN applications where smart devices are used. As radio communications are regulated worldwide, the use of Industrial/Scientific/Medical (ISM) radio bands is popular due to its exception to the licensing rule. The 2.4 GHz ISM band is allocated globally hence this will be used later in this thesis for simulations and performance evaluation.

This chapter provides an overview of the aspects of wireless sensor networks and scenarios that impinge, to some extent, on the design of effective medium access control (MAC) protocols. Section 2.2 places WSNs in context by relating them to different classifications, highlighting their characteristic parameters. Section 2.3 presents the different WSN applications, addressing their requirements and issues in network design, and the scenario for which the MAC protocols are being evaluated in this thesis. This chapter ends with a summary in Section 2.4.

2.2 Wireless Sensor Network Classifications

As the diversity of WSN applications is increasing, it is worthwhile to propose a structure for the set of characterisation parameters that allows a sketch of a taxonomy for WSNs to be drawn. This taxonomy is established via the category-oriented approach, identifying the specific service and requirement of each category of WSN applications. These characterisation parameters should be carefully considered in the process of designing medium access control (MAC) protocols. Most of the WSN literature offers analysis and classification using the traditional method, based on the medium access technique being used. Since applications can be defined as the tasks designated to the WSN, here we classify the WSNs by the characteristic parameters that extends from the traditional approach.

2.2.1 Characteristic Parameters

The wide diversity of WSN applications motivates the need for classification of their characteristic parameters. The role of a node within a WSN depends on the specific functions and behaviours they have been assigned. Here we define the roles of WSN device as:

Sensor Node - It is comprised of the sensors, microprocessor and radio transceiver. It measures physical phenomena and transmits to a data sink.

Sink Node - It can be a sensor node but with extended data processing capabilities, or it can be a different hub node that receives data from the sensor nodes of the WSN. Some sink/ hub node may also be tasked with managing the WSN.

Gateway Node - It is a node responsible for the connection and delivery of data to other communication networks.

A wireless sensor node is a device composed of several modules with sensing and communication capabilities. The radio transceiver enables each sensor node to access the wireless channel and communicate with other nodes within the sensor network. Wireless sensor nodes are also equipped with a finite power source. The overall energy consumption plays an important role in the WSN applications, with the need for a longer lifetime. The lifetime of the sensor node depends on the node sampling rate, which varies depending on the application, the power required for processing depending on the hardware, and most importantly the energy required for transmitting and receiving. However, what the nodes do with the information gathered is not a primary concern of the networking architecture.

There are different types of power supply that can be used in wireless sensor nodes. We can distinguish them into three energy sources: 1) battery, the most common way to power sensor nodes; 2) local supply, where nodes are connected to an uninterrupted and unlimited power supply; and 3) energy harvesting devices, which harvest energy from the surrounding environment (e.g., solar, vibrations, or wind).

2.2.2 Network Parameters

These are a group of network parameters that facilitate different WSN protocols. These parameters include network topology, lifetime, scalability, and maintainability, which are highly related to the application of the WSN. These parameters should be carefully considered when designing MAC protocols.

Topology - WSNs can be divided into two sub-groups: 1) Single-hop, and 2) Multi-hop. Single-hop communications can be considered as a form of centralised communication, where multiple wireless devices communicate with a central base station forming a star-based topology. All communications are directly between the device and the station, i.e. other devices cannot communicate directly. On the other hand, multi-hop communications can be considered as point-to-point communications, where wireless devices can directly communicate with neighbouring devices. This can also be used to relay data from one end of a network to another end. As radio communication is limited by the feasible propagation distance between the sender and receiver, a single-hop network might not be feasible for some specific WSN applications. To overcome such limitations, an obvious solution is to have additional relay nodes, with data packets taking multiple hops from the source node to the sink node. This can be carefully done with a suitable routing protocol at the transport layer. Finally, employing directional antennas can increase the transmission range.

Lifetime - The lifetime of the network is essential in WSN applications. The precise definition of lifetime varies depending on the application. A simple option is to define the network lifetime as the time until the first node fails, or the time until the network can no longer be fully operational (e.g. Too many nodes have failed, and the remaining nodes can no longer provide useful coverage). Since sensor nodes are mostly powered by batteries, a short lifetime can lead to frequent battery replacement/ recharge and a high maintenance cost. It is also worth noting that some WSNs might be deployed in hazardous, dangerous, or remote locations, where battery replacement or recharging might not be feasible. Hence, when designing a MAC protocol, lifetime/energy consumption of the sensor nodes must be carefully considered.

Scalability - Scalability can be considered as the ability of the WSN to support a high number/varying number of sensor node devices. Scalability of the WSN is enabled by the employed MAC protocol. If the node density of the WSN (the number of nodes within the network) is variable, the MAC protocol must ensure it can adapt to the changes.

Maintainability - Since the WSN and deployed environment can change over time, due to factors such as node density, failing nodes, or nodes out of range, MAC protocol adaptation is needed. The network must maintain itself even when some nodes fail to operate within the network. This is linked to the definition of the lifetime of WSNs. If the network can adapt and continue to perform whilst some nodes have failed, it can prolong the lifetime of the WSN application. This parameter is extremely important for WSN applications where a multi-hop topology or synchronisation is required.

2.2.3 Operational Environment Parameters

The operational environment characteristics define the context in which the WSN is deployed. Reliable radio communication links rely on sufficient link budget, in which an important factor is the propagation fading between the sender and receiver. It is worth noting that although single-hop networks provide a simple directional communication between the source node and sink node, it is not always a feasible option due to coverage difficulties limited by propagation distance.

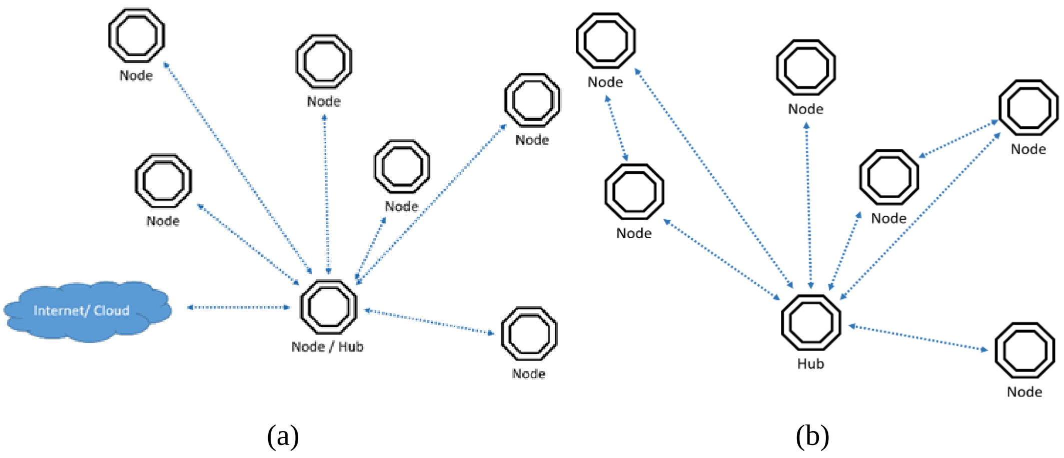

Figure 2.1. Different types of network architectures.

Figure 2.1 (a) considers the sink either as a normal sensor node in the network with no extended capabilities, such as a clustered network, or has extended capabilities such as a hub node, in a centralised star network. A clustered network is where a sensor node will be selected as a cluster head, in which it will act as a sink node. The node with the highest remaining energy is usually selected as the cluster head. One can also considers the sink node as a gateway node, with extended capabilities are being connected to other networks such as the internet or a cloud server. The concept of single-hop and multi-hop network is shown in Figure 2.1 (b). In a single-hop network, sensor nodes connect to the hub node directly, where sensor nodes form a relay network to convey packets for other nodes in a multi-hop network. While a multi-hop network architecture can overcome problems such as long-distance transmission or obstacles, it can require additional synchronisation or energy consumption. Detailed consideration should be taken when designing a MAC protocol for multi-hop networks, as a node must correctly receive a packet before forwarding it to another node. In this case, sensor nodes will be required to constantly listen to the channel for packets, with synchronisation or coordination possibly being required. Alternatively, researchers have been looking at applying directional antennas to sensor nodes or sink nodes to improve transmission distance. Besides, the trade-off between the maximum range of the sensor node and the network lifetime maximisation is always a critical decision. A centralised star network structure is considered in this thesis, since a hub node can represent a sink node in Figure 2.1(a). This is discussed in more detail later in this chapter.

For much of the remaining work and discussion, the distinction between these various types of sink nodes are actually irrelevant. It is however important to know whether the source nodes or the sink node are able to move. Although most WSN applications are static, meaning nodes are always stationary, one of the main virtues of MAC protocols is their ability to support mobile participants. In most WSN applications, mobility can be classified into two main forms:

Mobile Nodes - In this case the wireless sensor nodes are mobile. An example can be wildlife surveillance, where sensor nodes are connected to wild animals. Because of the node mobility, the network topology will constantly be changing, hence synchronisation might be required for some MAC protocols in order to operate properly.

Mobile Hub - In this case the sink node is mobile. An example can be a robot requesting information while moving in a warehouse where sensor nodes are attached to the shelves or parcels. As the sink node only communicates with the nodes within its vicinity, other nodes might be awake with no communication to perform. This must be carefully dealt with when designing the MAC protocol for these WSN applications as sensor nodes are required to know when the sink node will be within the vicinity for data transmission.

It is also worth noting that the MAC protocols must consider the speed of node movement as this can have significant implications (e.g. affecting the synchronisation frequency for contention-free protocols, or insufficient node transmission power). This can potentially lead to significant packet loss, resulting in poorer performance in comparison to static networks. These typical values of average speed for different scenarios are summarised in Table 2.1 [21].

Table 2.1. Typical values for average velocity from WSN applications entities.

Entity	Speed (ms^{-1})	Speed (miles/hr)
Mobile WSN nodes	0.1 – 1	0.2 – 2.2
Human (Walking)	1 – 2	2.2 – 2.5
Human (Running)	3 – 5	6.5 – 11.2
Car (Low Speed)	10 - 13	22 - 30
Car (High Speed)	18 – 35	40 - 80

2.2.4 Communication and Traffic Parameters

A large number of WSN applications follow an event-driven data delivery model. Most event-driven applications can be defined as interactive, low delay tolerant, real-time and unpredictable. Since most wireless devices are constrained in terms of battery, memory, processing capability and achievable data rate, efficient use of these resources is mandatory. Nowadays a significant number of applications have a data rate of 250 kbps. For example, the nominal transmission rate for the IEEE 802.15.4 standard components such as Crossbow MICAz [22] or Texas Instruments CC2520 [23] both operate at 250kbps. At the expense of higher power consumption, higher data rate can provide better link performance [24]. Whilst channel capability in wired networks is assumed to be pre-determined, in WSNs the radio channel can be divided into multiple sub-channels. Although multiple links can provide multiple simultaneous communications, a higher magnitude of power consumption might be required. Power consumption is a fundamental concern in WSNs, therefore the trade-off with respect to network performance and network lifetime must be carefully considered.

2.3 Applications

In this Section some WSN applications are presented. Table 2.2 and 2.3 present some indoor and outdoor applications, respectively.

Table 2.2. Communication and network parameters for indoor WSN applications.

Application	Smart Home: [8] [25]	Building Monitoring: [26]	Warehouse Tracking: [27]	Manufacturing: [28]	Personal Health Monitoring: [29] [30]
WSN Scenario	Single-Hop	Multi-Hop	Multi-Hop	Single-Hop	Single-Hop
Synchronisation	✓	✗	✓	✓	✓
Traffic Classes	Real Time / Delay Tolerant	Delay Tolerant	Delay Tolerant	Delay Tolerant	Real Time / Delay Tolerant
Lifetime	Long	Medium	Short	Long	Short
Mobility Support	✓	✗	✓	✗	✓
Scalability	✓	✗	✓	✗	✓
Communication Range	< 30 m	< 30 m	< 50 m	< 30 m	< 10 m
Power Supply	Battery & Local Supply	Battery	Battery	Battery & Local Supply	Battery

Table 2.3. Communication and network parameters for outdoor WSN applications.

Application	Wind Turbine: [31]	Bridge Monitoring: [32]	Aircraft Safety Monitoring: [33] [34] [35]	Disaster Monitoring: [3]	Disaster Monitoring: [36]
WSN Scenario	Single-Hop	Single-Hop	Multi-Hop	Single-Hop	Multi-Hop
Synchronisation	✗	✓	✓	✗	✓
Traffic Classes	Real Time / Delay Tolerant	Real Time / Delay Tolerant	Real Time / Delay Tolerant	Real Time / Delay Tolerant	Real Time / Delay Tolerant
Lifetime	Short	Long	Short	Short	Short
Mobility Support	✗	✗	✗	✗	✗
Scalability	✗	✗	✓	✓	✓
Communication Range	< 50 m	< 50 m	< 30 m	< 300 m	< 300 m
Power Supply	Battery	Battery	Battery	Battery	Battery

Traffic Class - All WSN applications transmit data traffic. The differences among those applications depends on the type of monitoring. Some real time monitoring applications, such as health monitoring and aircraft safety monitoring often have low packet delay tolerance due to the importance of the data being transmitted. The remaining real time and data monitoring applications such as smart home and bridge monitoring, are more delay tolerant, since either the data can be re-transmitted, or the sampling rate is frequent enough to provide reliable data delivery.

Synchronisation – It is worth noting that a lot of multi-hop WSNs and most real time applications require synchronized communication, with low packet delay tolerance, as accurate synchronisation is critical to ensure low delay and reliable transmission.

Lifetime - Although the majority of real time monitoring WSN applications appear to have high energy consumption, which can be misleading to assume a shorter lifetime, some applications such as bridge monitoring appear to be the contrary. This is because the sensor nodes have a low reporting frequency, the sampling rate and the reporting rate is low hence the nodes spend more time in idle, reserving energy. Some applications on the other hand have shorter lifetime, mostly due to high sampling rate and reporting rate.

Scalability - Some applications such as smart home and warehouse tracking require a high level of scalability, while some others such as bridge monitoring require no/low level of scalability. This highly depends on the nature of the WSN applications, but the MAC protocol must fulfil the requirements of the applications in order for the WSN to operate reliably.

Mobility Support - Due to the requirement of the applications, some WSNs might be required to support mobility. Hence, it is important for the MAC protocol to be able to handle sensor nodes or sink nodes manoeuvring at different speeds.

Power Supply - For most applications, sensor nodes are powered by batteries, whereas the sink node is assumed to be connected to a local supply (e.g., unlimited energy resources). Although it is possible for sensor nodes to be connected to the local supply for some WSN applications such as smart homes and manufacturing, for most MAC protocols the energy resources for the sensor nodes are limited.

2.4 Conclusion

This chapter provides an introduction to WSNs scenarios and applications. Some important information about different WSN applications have been put together to obtain insights about the possible applications requirements in order to design suitable MAC protocols accordingly. The requirements have been identified into characterisation parameters, where they need to be carefully considered. The aim for this chapter is to motivate the design of suitable MAC protocols to tackle these challenges. These parameters are then used to evaluate performances for MAC protocols. The design, analysis and performance evaluation of the MAC protocols presented in this thesis have focused exclusively on centralised star-based scenarios with a single hub and a single communication channel.

Chapter 3 Medium Access Control

Content

3.1 Introduction to Medium Access Control (MAC)

The majority of wireless communication systems incorporate some level of capacity sharing. In order to achieve capacity sharing in a wireless sensor network (WSN), multiple access techniques are required. The Medium Access Control (MAC) layer, a sub-layer to the data link layer of the International Standards Organisation – Open System Interconnection (ISO-OSI) reference model [37], is a mechanism for controlling the channel access of devices in a network through a shared medium. Almost all wireless networks require coordinated access from a group of users onto a single channel, with the exception of single point-to-point communication systems. A multiple access technique provides means of dividing channel capacity for simultaneous use by multiple users. Some well established multiple access techniques are the Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA), and Space Division Multiple Access (SDMA). MAC protocols regulate and control the access of the channel from multiple users by assigning the channel capacity to the users. MAC protocols are designed to coordinate packets transmissions from all devices, meeting the Quality of Service (QoS) requirements of different WSN applications, to provide the capability to resolve and prevent collisions during any contention period, but catering for the need for retransmission of packets received in error is considered in the logical link control layer. An example of a MAC protocol for a wired network is the Ethernet protocol, used in

Local Area Networks (LANs). This protocol employs Carrier Sense Multiple Access with Collision Detection (CSMA/CD) [38]. This thesis focuses on MAC protocols for wireless networks, more specifically, for wireless sensor networks (WSNs).

Chapter 2 has identified that whilst WSNs will continue to provide traditional monitoring services such as building infrastructure monitoring, they will also be required to support an increasing proportion of day to day applications in smart homes, smart warehouses, as personal health devices, etc. WSN capacity and energy budget are often limited resources, which must be as effective as possible to provide good performance. The achievable quality of service (QoS), channel utilisation and energy consumption are governed by the underlying MAC protocol. The MAC protocol is responsible for ensuring the application may provide good and fair performance whilst utilising the available resources efficiently and effectively.

This chapter covers background material on multiple access techniques and medium access control (MAC) protocols, and includes a comprehensive literature review of directional MAC protocols. Section 3.2 describes the fundamental multiple access techniques with particular emphasis on random access on which most of the research here is based. Section 3.3 details the alternative medium access control protocols and identifies their benefits and limitations, followed by some approaches for energy efficient MAC protocols in Section 3.4. Important design issues, constraints and performance criteria in directional MAC protocol design are discussed in Section 3.5, and in Section 3.6, a literature review of directional MAC protocols is given. The chapter ends with a brief summary in Section 3.7.

3.2 Multiple Access Techniques

There are four fundamental multiple access techniques for wireless networks. They are:

- Frequency Division Multiple Access (FDMA) [39]
- Time Division Multiple Access (TDMA) [40-42]
- Code Division Multiple Access (CDMA) [43]
- Space Division Multiple Access (SDMA) [44]

Most of the protocols that employ these four techniques require a degree of synchronisations with users transmitting on orthogonal channels, separated in frequency, time, code or space respectively. Contention-free or scheduled-based MAC protocols attempt to organise sensor nodes within the network so their communications may occur in an orderly way. Organising sensor nodes requires knowledge of the network such as the topology, node density, mobility and retransmission management. This is achieved by synchronisation and effective allocation. The SDMA technique is a multiple access technique proposed for the smart antenna based WSNs. Random access represents contention-based multiple access with little or no coordination of user transmissions. Some hybrid protocols may employ multiple channel access techniques, enabling them to be integrated with SDMA and contention-free TDMA-like transmissions. In these cases, a hybrid technique where the contention-based access represents the access strategy to the SDMA channel instead of a pure access technique is employed.

3.2.1 Frequency Division Multiple Access (FDMA)

FDMA is a traditional contention-free technique where wireless devices transmit simultaneously on different carrier frequency bands. It is important to ensure that each wireless device has sufficient separation in frequency, in ensuring that there is no interference to the adjacent channels. Figure 3.1 shows the basis of the FDMA technique. The guard bands in FDMA are introduced to compensate for the offsets in the nominal carrier frequency, and to ensure that there will not be excessive interference to adjacent devices.

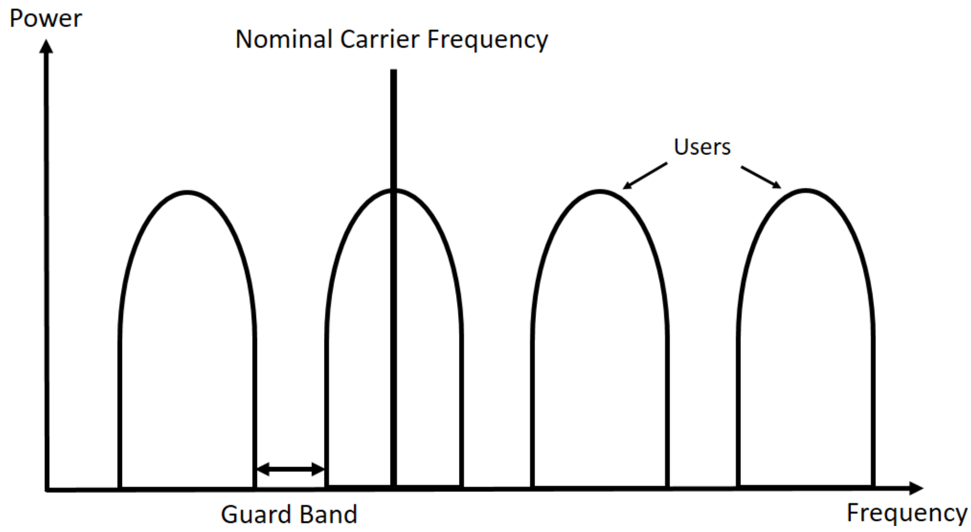

Figure 3.1. Frequency Division Multiple Access (FDMA).

In as FDMA network, individual devices are assigned to a designated frequency channel which can be used for communication. The advantages of FDMA are that it is cheap and simple to implement. As each device is assigned a unique channel for transmission, no coordination or synchronisation is required. It is also worth noting that the maximum number of devices supported by FDMA is limited by the number of channels available. In order for devices to be added to a FDMA network, the devices are required to be equipped with either multiple transceivers or the transceiver needs frequency agility. It is also difficult to assign different bandwidths to different devices based on their requirements, as there will be devices operating on adjacent frequency bands.

3.2.2 Time Division Multiple Access (TDMA)

In the TDMA technique, the channel is time shared, on a fixed basis. This technique precludes fluctuations in the number of wireless devices in the network. It allocates regular time-slots in which bursts of data may be transmitted in a contention-free basis. It is a popular technique in particular, if each device in the network emits a steady flow of data in which the message interarrival times for each device have low variance. It is also worth noting that TDMA can suffer long delays in scenarios where network traffic is dynamic, due to timeslots being unnecessarily assigned to idle users with no information to send. Figure 3.2 illustrates the TDMA technique. Guard times are introduced in a TDMA network to ensure that there is no overlap between transmissions due to different propagation delays or inaccurate time synchronisation. The guard bands in FDMA and the guard times in TDMA introduce a degree of inefficiency to the protocols as these are not used for constructive transmission. Accurate time synchronisation is important in TDMA to ensure no overlap between transmissions from different devices. This is normally achieved by regular beacon transmissions from the receiver as a reference, used by others devices to synchronise its time. Although TDMA schemes have appealing features, they have some shortcomings resulting from their dependency on the network topology and time synchronisation. A given network topology is used to establish a collision-free arrangement and tight synchronisation to ensure a common schedule among nodes. Both knowledge of the topology and strict synchronisation require large overheads and/or expensive hardware and hence renders TDMA solutions less attractive in large-scale rollouts.

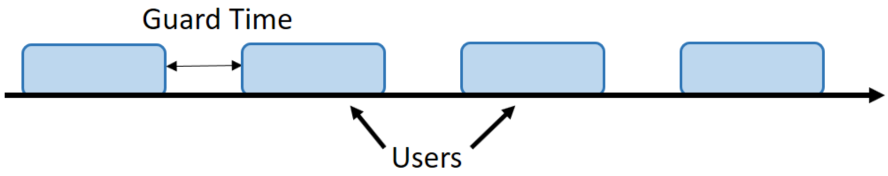

Figure 3.2. Time Division Multiple Access (TDMA).

There are some advantages of using TDMA over FDMA. Firstly, TDMA is more suited to applications with regular data traffic. Data packets that are generated from clocked devices at specific instants in time could be easily supported by the TDMA technique. Secondly, FDMA lacks flexibility in both network scalability and network reconfiguration. In contrast, TDMA can assign transmission time dynamically to different devices based on their requirements, although regular synchronisation may be required. Devices can also be added to the network without additional hardware requirements. However, sensor nodes operating under a TDMA based protocol must have sufficient power to transmit at a high data rate for short periods of time, whereas sensor nodes under a FDMA based protocol transmit with continuous low data rate.

3.2.3 Code Division Multiple Access (CDMA)

CDMA is a technique that utilises spread spectrum modulation. The CDMA technique modulates data packets with a noise-like broadband waveform, therefore it will spread the signal power over a wide frequency band. CDMA techniques were originally used for applications that require anti-jamming, anti-interference and low probability of interception. There are two types of CDMA technique: direct sequence and frequency hopping. In direct sequence, each transmission signal is multiplied by a unique bandwidth spreading code to generate a strong signal that occupies a wider bandwidth. A distinct spreading code (waveform) with a low cross-correlations is used to allow multiple devices to communicate simultaneously using a common carrier frequency. On the other hand, the frequency hopping technique divides the available frequency band into smaller sub-bands. Transmissions rapidly change their carrier frequency among the sub-bands (also known as frequency hopping) to avoid interference and interception. These changes are controlled by a spreading code only known to the transmitter and receiver.

The advantages of CDMA are that it offers good performance against fading, noisy or interference heavy environments. The de-spreading process at the receiver serves to spread the uncorrelated data from the unwanted sources, which limits the interference to the wanted data transmission. As it requires the spreading code for the receiver to de-spread the packets, CDMA has a high security level for data transmission. However, as the number of devices in the network increases, the performance of CDMA will be limited.

3.2.4 Space Division Multiple Access (SDMA)

SDMA is a technique that spatially divides the network environment. It was designed for networks where the hub/receiver has multiple directional antennas. This potentially allows the network throughput to be multiplied by the number of antennas equipped at the receiver, without needing additional hardware on the devices. Atmaca *et al* described a SDMA MAC protocol in [17], in which the link capacity improvements are evaluated. Figure 3.3 shows the directional antenna models with reference to antenna sector, adaptive array antennas, and switch based antennas. In a sectorised WSN, the network is divided into equal sectors, in which the number of sectors is equal to the number of directional antennas. Sensor nodes located in these sectors are only allowed to communicate with the directional antenna in this sector to reduce the interference to adjacent antenna sectors. In an adaptive array system, the direction of the main lobe can be adjusted by concentrating the energy in a particular direction, providing more flexibility compared to sectorised system and switch based system. In a switch based system, one of the antenna patterns is chosen from many for communication with particular sensor nodes, usually the one with the high antenna gain or SINR.

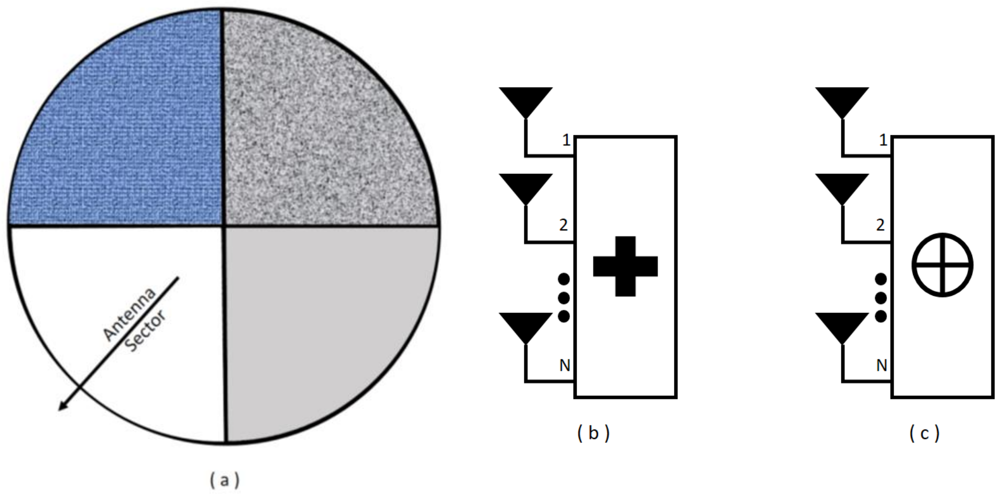

Figure 3.3. Directional antenna model, (a) Antenna sectors, (b) Adaptive array function, (c) Switch based function.

3.2.5 Capacity Assignment

Capacity Assignment can be considered as a more flexible form of technique. The capacity assignment techniques can be generally categorised into two types: fixed assignment and demand assignment.

3.2.5.1 Fixed Assignment

Fixed assignment provides pre-assigned and periodic time slots for each device. MAC protocols with TDMA or a polling technique can be considered as fixed assignment. Figure 3.4 presents the fixed assignment strategy. Although fixed assignment can provide fair access to all devices, the static nature of the assignment may deem it inefficient under dynamic scenarios where the number of sensor nodes or load of traffic vary significantly overtime. When a device does not have any data to send, such assigned capacity will be unused and wasted. However, the regularity of the assignment is efficient in scenarios where the traffic demand is highly regular and constant over a long period of time. The advantage of fixed assignment over contention-based protocols is that it can provide absolute guarantees on zero collision probability, but at the expense of longer delay.

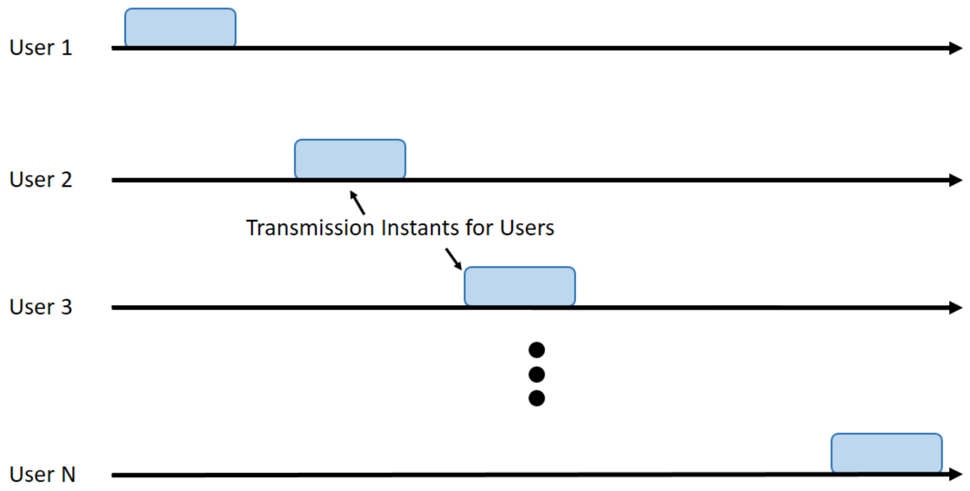

Figure 3.4. Fixed assignment strategy.

3.2.5.2 Demand Assignment

Demand assignment allocates capacity in response to the device requests. An example of a demand assignment strategy is shown in Figure 3.5. Individual devices can make requests for slot assignments based on their traffic requirements; they can request a specific number of slots/durations to suit their needs based on their current queue level. A high channel utilisation can be achieved with this strategy as the capacity is allocated to match the individual requirements. However, this can introduce significant delay between the request and the assigned slots. The demand assignment sometimes requires a request channel, which may call for additional hardware and energy requirement on the devices.

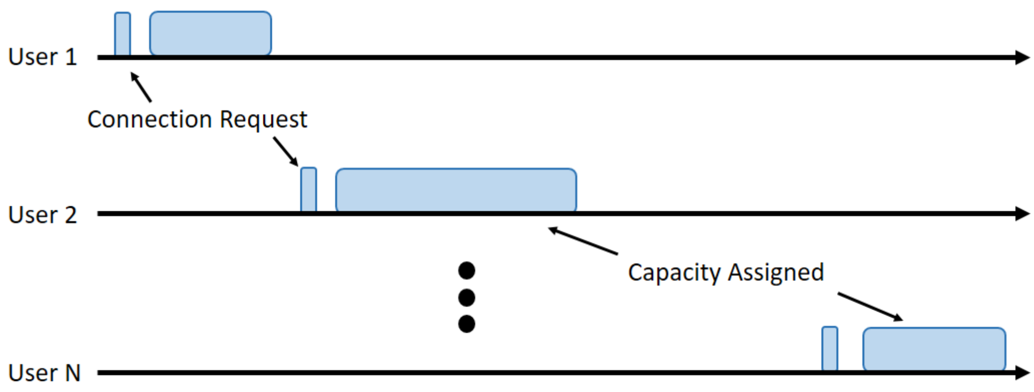

Figure 3.5. Demand Assignment Strategy.

3.2.5.3 Random Access

Differing from the other assignment strategies, random access techniques take a different approach than operating with a scheduler. In random access, devices themselves may decide when to transmit on the channel. Random access techniques were one of the first to be used in packet-switched communication networks. One of the first random access protocols was The Aloha protocol, which was developed at the University of Hawaii to allow data to be transmitted between sites [45, 46], and it has since inspired a significant of amount of research, analysis and development [41, 47-51].

There are two standards of Aloha protocol: The Pure Aloha and Slotted Aloha protocols. In the Pure Aloha protocol, devices can transmit packets using a shared channel as soon as the packets arrive in the queue, providing there is no on-going transmission. As there is no coordination required between devices to access the channel; if more than one device transmits at the same time, a collision will occur, and data may be lost. For a reliable network, a receiver will transmit acknowledgements back to the sender following the successful reception of data, enabling the sender to determine whether a collision has taken place and if retransmission are required. The senders wait for acknowledgements for their transmitted packets and if they do not receive them within a specified time duration, they will enter a timeout period followed by retransmission. If the sender re-transmits the packet immediately after failure to receive the acknowledgement, it is likely that it will collide again hence a randomised backoff strategy is needed. This process is repeated until either the transmission is successful or it reaches the retransmission limit. Pure Aloha is an effective strategy for WSNs with low traffic load and irregular transmissions. If devices only need to send occasional short packets, the probability of successful transmission is high and low end-to-end delay values can be achieved. The maximum channel throughput achieved with Pure Aloha is approximately 18.4% of the channel capacity. Figure 3.6 and Figure 3.7 show examples of packet reception of both the Pure and Slotted Aloha protocols.

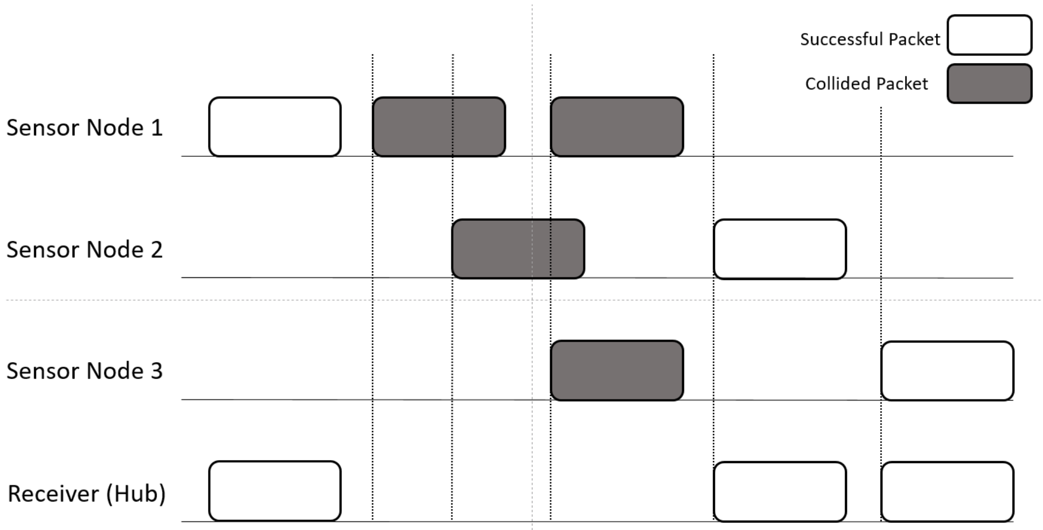

Figure 3.6: An example of packet reception with the Pure Aloha Protocol.

Slotted Aloha is an extension from the Pure Aloha protocol, which can potentially provide twice the maximum channel throughput, with increased protocol complexity. In the Slotted Aloha protocol, time is synchronised and divided into slots with a duration equivalent to the packet transmission time and a short guard time. Devices transmit data packets at the beginning of time slots following their arrival. As a result, collisions only occur if more than one user transmits in the same slot. The decisive difference between the Pure Aloha and Slotted Aloha protocols is the period in which packet collisions are possible, two packet durations for Pure Aloha and one packet duration for Slotted Aloha. This difference halves the packet collision probability and results in a doubling of the throughput capability. A detailed analysis of the throughput performance of Pure Aloha and Slotted Aloha protocol, including the theoretical throughput and simulation results is given in Chapter 5.

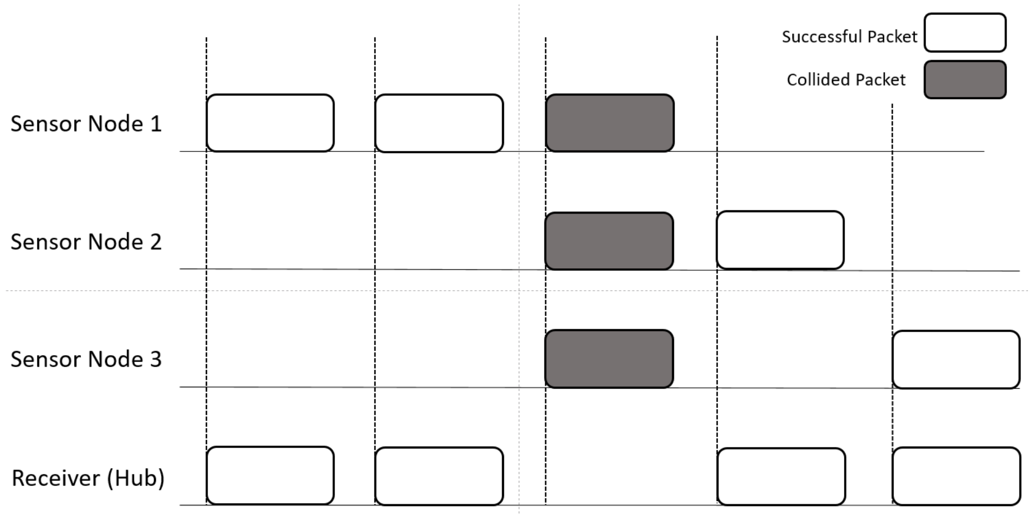

Figure 3.7. An example of packet reception with Slotted Aloha Protocol.

Following the development of the Aloha protocols, numerous random access techniques have been developed. An example of another random access technique is Carrier Sense Multiple Access (CSMA) [42], which can be considered as a variant of the TDMA technique. In the CSMA protocol, a node senses the channel for ongoing transmissions. If the channel is sensed idle, the node will begin the transmission. If the channel is busy, the node will enter a backoff process for a random duration before attempting to transmit again. As no single capacity assignment strategy is able to provide low delay transmission, high efficiency and throughput, MAC protocols which combine more than one capacity assignment strategy have emerged. These hybrid strategies adopt dynamic strategies to suit the specific requirements for different applications. An example of such MAC protocols with hybrid strategies is later shown in Section 3.3.3.

3.3 MAC Protocols for WSNs

MAC protocols for wireless networks have been subjected to extensive research and development for the last few decades, and a number of examples will be described in this section. MAC protocols can be broadly categorised into contention-based protocols and contention-free protocols based on the multiple access technique employed. Traditional MAC protocols consider a combination of channel utilisation, throughput enhancement, energy consumption and delay minimisation, depending on the specific application requirements. Contention-free protocols can dynamically assign transmission schedules, achieving high throughput and low collisions at the expense of higher complexity and latency. On the other hand, contention-based protocols suffer from higher levels of overhearing, collisions and retransmissions, but lower end-to-end delay. Overhearing refers to the phenomena where sensor nodes other than the intended recipient of a packet may overhear (receive) the transmission. There are also a number of hybrid MAC protocols which combine both contention-based and contention-free techniques.

Some of the more prevalent MAC protocols are described in this section, with particular emphasis on random access behaviour. The intention is to provide a description of the important features and concepts of each scheme. One of the challenges of WSNs is the dynamic traffic demand and varying number of devices in the network. Contention-free MAC protocols generally have limited applicability to these WSNs as the delay and synchronisation requirements are much higher than contention-based MAC protocols. It is therefore common to employ a contention-based or hybrid MAC protocol which combines multiple channel access techniques.

3.3.1 Contention-based MAC Protocols

In contention-based MAC protocols, nodes contend to gain access to the channel. As mentioned earlier, the Pure Aloha protocol is the earliest contention-based protocol. If more than one device transmits simultaneously, packet collisions will occur at the receiver. Since then a number of contention-based MAC protocols have been developed such as many CSMA based protocols. However, although the CSMA technique tries to avoid collisions through physical carrier sensing, a further extension with virtual sensing has been proposed: Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). This extension aims to deal with challenges such as packet collisions caused by the hidden node problem later described in this chapter.

Many CSMA based protocols exist, which differ according to the action that a sensor node takes to transmit a packet after sensing the channel. In all cases however, if a sensor node wants to transmit data, it begins by sensing the channel [52]. If the channel is sensed busy, then it will defer transmission. On the other hand, if the channel is sensed idle for a specific period of time, i.e. the Distributed InterFrame Space (DIFS) from the IEEE 802.11 DCF [53], then the sensor node is allowed to transmit. In cases where reliability is required, the receiver returns an acknowledgement packet (ACK) to the transmitter upon receiving the data packet successfully. If the transmitter does not receive the ACK within a short time, it will retransmit the data packet until an ACK is received or the retry limit is reached.

Since the development of the CSMA/CA protocols, extensive research has been conducted, for example with regard to the backoff strategy [54] and energy consumption [55]. The CSMA/CA/DCF protocol is a variant of the CSMA/CA protocol [53]. Similar to the original CSMA mechanism, a sensor node wanting to transmit data will first wait for a predefined period, here denoted as the DCF Interframe Space (DIFS) of 50 μs. Figure 3.8 presents the CSMA/CA/DCF channel access procedures. If no transmission is detected during this period of time, a Clear Channel Assessment (CCA) will be sent to the MAC layer and the sensor node will wait for an additional random duration, also known as the Contention Window (CW). If no transmission has been detected during this period, the sensor node will send a Request-to-Send (RTS) to the receiver. This short control packet contains the MAC address of the transmitter and the receiver. It also contains the estimated duration of the data packet. This allows the other sensor nodes to determine their Network Allocation Vector (NAV (RTS)). The NAV defines the time required to complete the subsequent transmission and associated handshaking. During this period, the adjacent sensor nodes are not allowed to transmit to avoid collisions. After a Short InterFrame Space (SIFS) of 10 μs, the receiver will send a Clear-to-Send (CTS) to indicate the transmitter that it is ready to receive the packet and the channel is reserved. This control packet also contains an important information that allows adjustment the NAV (CTS). At this stage, the reservation procedure is completed and the transmitter will send the data to the receiver. The receiver will then acknowledge the packet by sending an ACK. If the transmitter has not received the ACK, it will send the data again. A SIFS period separates each control packet and data packet exchange to avoid any overlap.

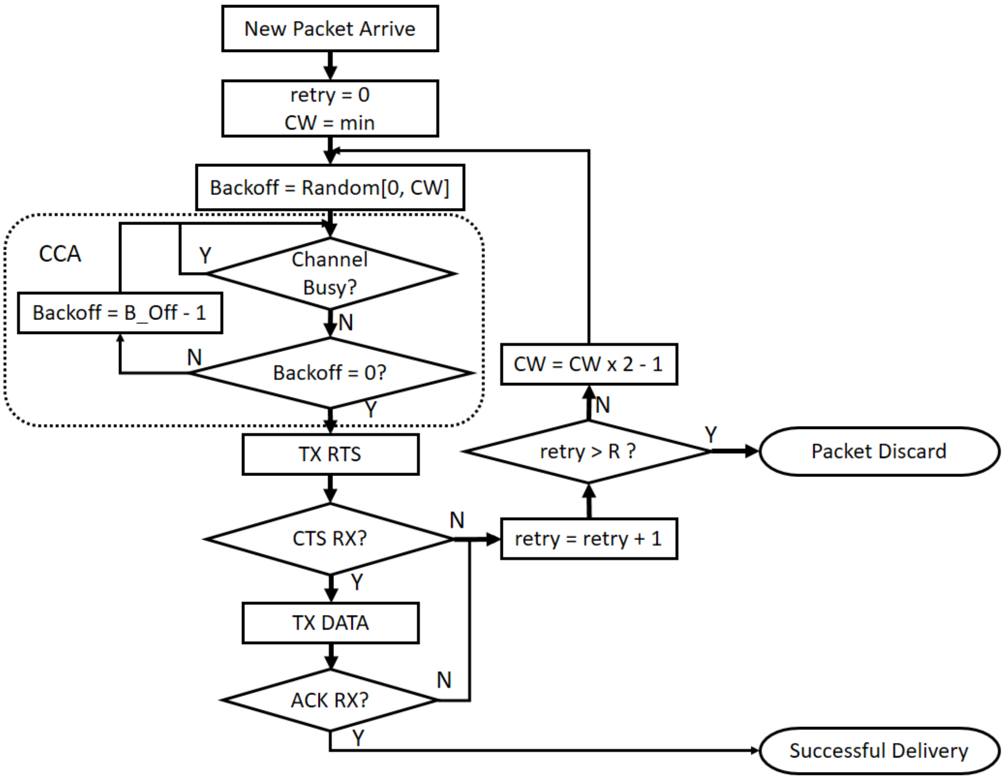

Figure 3.8. CSMA/CA/DCF channel access procedures.

If the channel is sensed busy during the contention window, the counter that holds the remaining time of the backoff (B_Off) is frozen until the channel becomes idle again and resumes counting down. A Binary Exponential Backoff (BEB) algorithm is used in the CSMA/CA/DCF protocol to resolve contention between different sensor nodes wanting to access the channel. The algorithm requires each sensor node to choose a pseudo-random number (n) between 0 and a given maximum number, and wait for this number of slots before accessing the channel. The duration of the slot time is defined in such a way that a sensor node will always be able to determine if another sensor node has accessed the channel in the previous slot. The exponential backoff scheme means that each time a sensor node chooses a slot and happens to collide, it will increase the maximum number of the pseudo-random number selection exponentially until it reaches the maximum retry limit (R) or the maximum CW value. This BEB scheme must be executed in situations where the channel is sensed busy before the sensor node first transmits a packet, after a failed transmission, or after a successful transmission. The handshaking and channel reservation technique eliminates some challenges posted by the original CSMA protocol such as the hidden terminal problem. The challenges and restraints on MAC protocols will be discussed later in this chapter.

A modified Markov model including retransmissions with finite retry limits and beacon-enabled sensor nodes has been studied in [56]. It attempts to model the slotted CSMA/CA mechanism with beacons. Most carrier sensing MAC protocols assume uniform probability in terms of channel states. However, it is shown that the probability of a sensor node sensing the channel to be free is not a constant during all stages, but instead depends on the number of sensor nodes sensing the channel at the same time. These differences have a noticeable impact on the performance metrics of the MAC protocol, as the throughput and the probability of packet collision are affected as a result. The impact on performance from this assumption is discussed in this study and an extended Markov model is presented.

Another widely studied contention-based protocol is the Sensor MAC (SMAC) protocol [57], a RTS/CTS based protocol with the concept of duty-cycle in which the device in the network periodically sleeps, wakes up, performs sensing, transmits data, and returns to sleep. The primary advantage of SMAC is the reduction of energy consumption from the various sources such as unnecessary channel sensing, overhearing, and control overhead. However, some nodes in SMAC are required to act as virtual cluster heads. These nodes have a higher energy consumption as they have to frequently transit into the listen state, hence reducing the lifetime of the network. It is also difficult to ensure that there are an appropriate number of cluster head present in the network.

3.3.2 Contention-free MAC Protocols

In contention-free MAC protocols, knowledge of the network topology and scheduling information are usually required to allow each node to access the channel. These scheduling techniques may have different goals such as ensuring fairness among nodes, reducing collisions, or avoiding multiple nodes accessing the channel at the same time. TDMA is one of the representative examples for such approach.

Low Energy Adaptive Clustering Hierarchy (LEACH) is a TDMA based protocol integrated with clustering and routing techniques [58]. LEACH is a self-organizing MAC protocol with the objective to reduce sensor node energy consumption. The basic concept of the LEACH protocol is to divide nodes into clusters within the network, in which one node is nominated as the acting cluster head of each cluster during the set up phase. Each cluster head is responsible for coordinating the cluster and the schedule of TDMA within the cluster. The role of cluster head is randomly rotated among the sensor nodes within the cluster based on the remaining energy left in each cluster head to equalise the energy dissipation of each node. No peer-to-peer communication is allowed in LEACH. As the sensor nodes transmit their data using a TDMA slot schedule assigned by the cluster head, nodes will switch to sleep mode when they are not scheduled to transmit or receive to conserve energy. Cluster heads will relay data packets to other nodes, a cluster head, or the sink based on the requirements of the packet. A unique CDMA code is used by each cluster to avoid interference with adjacent clusters. This is broadcast to all nodes during the setup phase. However, as the cluster heads are picked randomly, there is a chance some nodes would be out of range of the cluster heads and that the number of cluster heads might not be sufficient.

Z-MAC [59] is an example of a multi-hop protocol using the advantage of CSMA techniques. It uses the CSMA protocol when traffic offered load is low and the slotted TDMA protocol when traffic offered load is high. During the set-up phase, each node in Z-MAC broadcasts a ping to all its one-hop neighbours to gather a list of its neighbour nodes. The ping message from other nodes will also contain the one-hop list so each node will have a two-hop neighbours list at the end of the set-up phase. Using this list, a distributed slot assignment algorithm is used to make sure only one device within the two-hop neighbour list is given to each slot. If the device has nothing to transmit, then other devices may borrow the free slot through competition (CSMA).

3.3.3 Hybrid MAC Protocols

Hybrid MAC protocols take advantages from both contention-based and contention-free techniques. A hybrid MAC protocol described in [60] is an extended version of the TDMA and CSMA/CA hybrid protocol, where the SDMA technique is used to assign the timeslots for the TDMA procedure. A control parameter (P) is introduced which specifies the transmission power of the beacon from the hub node to other sensor nodes. The WSN is divided into zones with the hub node at the centre. With different levels of P, the beacon will only be reserved by sensor nodes at designated zones. After using the SDMA technique to group nodes into subnets using different transmit powers, different timeslots are allocated to the different subnets for the TDMA. Nodes will then contend for access with other nodes within the subnet during the assigned timeslot with the CSMA/CA technique. This protocol is designed for WSN applications where periodic data transmissions are not frequent but the network has unpredictable data transmissions. This access procedure allows the WSN to be divided into smaller subnets with low node density, where nodes within the subnet have less contention and lower delay when needed to access the channel. Similar to the MAC protocols described in [61] and [62], sensor nodes are allowed to spend more time in the idle state instead of performing continuous channel sensing. This reduces the energy consumption of the sensor nodes and extends the network lifetime. However, periodic synchronisation is required at the beginning of each timeframe for the SDMA and TDMA techniques. It is also worth noting that this provides improved throughput performance and energy efficiency, and this protocol also considers the effects on these metrics for mobile WSN applications.

3.3.4 MAC Protocol Design Challenges and Constraints

Unique properties of the wireless medium make the design of wireless MAC protocols very different and more challenging than wired networks. Many important issues in the protocol design have to be addressed at the MAC layer. Certain challenges and constraints are discussed in detail as follows:

Hidden node - When applying protocols such as CSMA, some devices may not be within the range of each other, where two or more devices may have a common neighbour while they are out of range with each other. If both devices sense the channel to be free and try to transmit to the common neighbour at the same time, then a collision will occur at the receiver.

Exposed node - The exposed node problem is the opposite of the hidden node problem. This occurs when a sensor node is prevented from transmitting due to potential interference from a neighbouring transmitter. The RTS/CTS handshaking mechanism from the CSMA/CA protocol partly overcomes the hidden node and exposed node problems by using the CTS message from the receiver to alert sensor nodes about the ongoing transmission pair.

Fairness - An important characteristic of a MAC protocol is to provide fair channel access among all competing nodes. In a fair scheme, sensor nodes should have equal probability of accessing the channel successfully regardless of the location of sensor nodes. However, most existing trends focus on the design of the MAC protocol to optimize other performance metrics such as throughput, in which high throughput performance does not reflect the fairness of a WSN.

Stability - The ability of the MAC protocol to cope with fluctuations in the level of channel traffic without entering an unstable state is an important feature. Stability is a serious issue for contention-based random access protocols, where a rise in the channel traffic increases contention, placing a large number of sensor nodes into a state of retransmission caused by collisions, with minimal useful throughput. A well designed protocol should be able to handle instantaneous channel traffic levels greater than the maximum sustainable load without undesired performance.

Capture Effects - It is common for some researchers to assume that if two devices transmit simultaneously over the same channel, a collision will occur at the receiver. Therefore, concurrent transmissions may result in packet collision and reception failure of all collided packets. The capture effect can be defined as the ability for the receiver to receive a packet correctly when simultaneous reception occurs. The packet with a stronger signal can be successfully received, providing the received power is sufficiently larger than the sum of the other signals, which can be considered as noise or interference. The performance metric signal-to-interference-plus-noise ratio (SINR) is essential here, as if the packet SINR is above the critical threshold, the packet is captured/received.

Power Management - In any wireless system, it is always desirable to maintain a low energy consumption for all devices as most devices operate with limited resources. Low energy consumption leads to longer network lifetime and lower maintenance, as the need for battery recharging or replacement is lower.

Scalability - It is important to have a MAC protocol that provides a degree of flexibility in the number of sensor nodes that the WSN can support, allowing the facility to add and remove sensor nodes with the network. Scalability can be challenging with scheduled-based MAC protocols, where a change in number of users requires re-configuration or re-synchronisation. Being able to provide service in the presence of sensor node failures and changes in number of sensor nodes are also important factors for MAC protocols designed for multi-hop WSNs. The ability of the scheme to continue to support a wide range of sensor node population sizes should be considered when designing a MAC protocol. For some MAC protocols, frequent re-synchronisation might be required to reconfigure the network regularly to adapt the continually changing network density.

As a result of these properties, the design of the MAC protocols in this thesis have taken into account a number of factors. These factors include reducing the effect of exposed node problems to improve throughput and reduce delay, and developing a power control strategy to improve the energy efficiency and reduce the capture effect. Section 3.5 describes the specific constraints and desirable attributes of directional MAC protocols.

3.4 Energy Efficient WSNs Review

In this section, literature on WSN energy consumption and energy efficient MAC protocols are studied and compared. Since the transmission power of the transmitter is a crucial factor in wireless communication and radio propagation, the energy consumption of the sensor node must be carefully considered in order to properly evaluate the overall performance of a WSN. It should also be noted that low energy consumption, rather than low power consumption, is a critical issue for any battery operated devices such a wireless sensor nodes. Although there have been efforts to produce more energy efficient sensor nodes, energy consumption during transmission and reception remain the highest proportion of the overall sensor node energy consumption [63]. The main sources of energy consumption in MAC protocols are: idle/sleep, channel sensing, packet transmission, and packet reception. Delays and packet collision are some influencing performance metrics which can decease the network lifetime and stability. Depending on these parameters, different approaches at the MAC layer have been studied to overcome these constraints, improve node energy efficiency and prolong network lifetime under limited resources.

The study in this thesis considers a centralised WSN where nodes transmit to a single hub node, without any intermediate nodes. Although the transmission distance for these direct transmissions may be longer than some other protocols such as multi-hop based protocols, nodes are not required to be awake in order to relay packets from other nodes. The power consumption for the transmission might be higher but the overall energy consumption of the node may be lower than multi-hop counterparts. Studies [64] have demonstrated that improper configuration and design of a MAC protocol can lead to poor performance in terms of energy efficiency and delay.

3.4.1 Energy Consumption Analysis

A comprehensive study of different techniques and mathematical expressions are included in this section in order to analyse the energy consumption characteristics of different channel access techniques.

In order to reduce sensor node energy consumption and improve network lifetime, good knowledge of the sources of energy consumption in WSNs is one of the key steps. Therefore, accurate energy models for different MAC protocols are essential for different WSN applications.

A wide range of literature describes energy consumption modelling and lifetime estimation [65-70]. Numerous studies have discussed the potential of solving the issue of energy consumption in WSN by designing an exploiting the MAC layer effectively. Establishing and maintaining a successful wireless communication link whilst achieving all the Quality of Service (QoS) requirements is challenging, since the energy consumption requirements of the sensor node are different for different WSN applications. Thus, the trade-off and the balance between QoS and energy efficiency has been of increasing research interest. These QoS metrics include delay, throughput scheduling and scalability etc.

3.4.1.1 Energy-Latency Trade-off

Channel access is an important aspect in any wireless communication system. An approach has been described in [71] with the aim to provide a trade-off analysis between energy and latency performance. The Geographic Random Forwarding (GeRaF) protocol attempts to improve network QoS based on collision avoidance and a duty cycling approach. In this scheme, each sensor node has a means to determine their location and the location of the destination. Nodes can volunteer to act as a relay, not within the routing protocol but by the means of the RTS/CTS exchange from the collision avoidance mechanism. A duty cycle strategy is also enabled to allow nodes to enter sleep mode and wakeup without synchronisation. A scheduling algorithm is proposed in [72] to find the minimum delay given the timeslot length of all communication links. The objective of this algorithm is to weight the sum of the delay and the total energy consumption in order to find the optimal delay-energy trade-off.

3.4.1.2 Energy-per-Bit Trade-off

To measure and compare the energy efficiency of different MAC protocols, one can choose a performance metric, such as the energy required to reliably deliver one bit of data successfully. The trade-off between transmission energy and SINR has been studied in [73, 74], in which the energy-per-bit requirement can be minimised if the WSN is operating at a low SINR in order to maximise energy efficiency. Dynamic transmission power control based on the channel conditions can achieve the balance between required transmission energy and SINR for successful delivery.

3.4.1.3 Energy-Throughput Trade-off

The study in [75] characterises the throughput and energy consumption trade-off. An analytical model has been proposed for single-hop WSNs to determine to trade-offs between energy saving requirements and QoS metrics such as throughput performance. A similar study has been presented in [76] for the energy efficiency and QoS trade-off, in which a dynamic energy management method has been proposed as a function of the channel traffic load. If the WSN is in a low traffic load scenario, a high QoS is achievable due to the large surplus of available radio resources and the focus should be on the energy efficiency instead of network throughput. On the other hand, in a heavy traffic load scenario, where the lack of radio resources requires more attention to be paid to channel access and allocation, the focus should be on throughput and the energy consumption becomes less important. The dynamic trade-off allows the scheduler to adjust its priorities based on the activity on the channel, providing dynamic energy management whilst maintaining throughput performance.

3.4.1.4 Energy-Bandwidth Trade-off

To provide a Green Transmission Technologies (GTT) solution to the growing worries surrounding WSN energy consumption, Wu *et al* describe the trade-off between spectrum efficiency and energy efficiency in [77]. Focusing on the MAC layer radio resource management in WSN, GTT solutions can utilise the different resources to achieve a balance in the trade-off between energy and spectrum efficiency. The study provides a solution with bandwidth expansion. Although based on Shannon's formula, expanding the transmit bandwidth reduces the transmit power required. Available spectrum is limited and when the WSN is under heavy load, and the bandwidth allocated to each sensor node may not be expandable. Hence, a dynamic solution has been proposed, where a weight value is chosen based on the available bandwidth and sensor node energy. Multiple-In-Multiple-Out (MIMO) systems play an important role in wireless communication today. If multiple antennas are applied to the WSN, it can be regarded as a MIMO system. Multiple antennas allow simultaneous communications with multiple frequency channels at each node, in which throughput and delay performance can be improved. However, operating multiple antennas simultaneously will have a significant impact on node energy consumption.

3.4.1.5 Energy-State Trade-off

To improve the energy efficiency of WSNs, energy efficient duty cycled MAC protocols are designed to put sensor nodes to sleep. A study in [78] by Jurdak *et al* describes a low power sleep mode MAC protocol based on the current network traffic conditions. The trade-off between the sampling rates and network traffic load with the energy consumption of the nodes have been discussed. A deep sleep mode that has a low current draw contributes to improving the network lifetime. However, it comes at the cost of high latency and energy cost to switch the sensor node to active mode, while the idle mode has quicker and inexpensive switching to the active mode.

3.4.2 Energy Models and Lifetime Estimation

An energy model for contention-based MAC protocols such as the CSMA/CA technique is described in [79]. Although in protocols such as CSMA/CA, sensor nodes consume more energy while using the channel sensing technique, it increases the reliability and throughput performance. Hence, the authors investigate the energy consumption for sensor nodes with different modulation schemes and corresponding error probabilities while employing the carrier sensing technique. An energy consumption model for determining the power consumption in delivering one bit of data successfully between two sensor nodes is described. An investigation for most efficient transmission power for each modulation schemes is then provided. As a result, an efficient node transmission power model as a function of error probability is proposed for contention-based MAC protocols. However, there is limited scope for flexibility and adaptability for this energy model due to the restrictive and relatively static traffic scenario.

The node energy consumption model for contention-based protocols is further developed in [80], by Agarwal *et al*. A formulation to compute the energy consumption per operation cycle is first described. This provides an estimation of energy consumed per transmission by the sensor nodes. In order to provide a network lifetime estimation, a method to determine the lifetime bounds for sensor nodes is proposed in this study. As the maximum number of operating cycle of a sensor node depends on the energy consumed over each cycle. The upper bound for the sensor node lifetime can be determined by having the best-case energy consumption scenario where all operation cycles have the least a (minimum) energy consumption. On the other hand, the lower bound can be determined by having the worst-case scenario, in which all operation cycles have the maximum energy consumption. An energy consumption model and lifetime estimation have been proposed for contention-based MAC protocol such as CSMA/CA. These models provide realistic estimates of WSN lifetimes, as a function of sensor node lifetime and the operations states of the sensor node.

Although the energy models described in this subsection have provided several good methods for the estimation of the energy consumption and lifetime for contention-based MAC protocols; these approaches would need to be modified in enabling its adaptation towards dynamically changing traffic demand and number of device scenarios which are highly relevant in this thesis.

3.4.3 Optimising Energy Efficiency

Extensive research have been conducted in the development of energy efficient and reliable MAC protocols for WSNs. Different researchers use contention-based protocols for WSN applications. One of the major drawbacks for contention-based protocols such as CSMA/CA is the high node energy consumption due to the continuous channel sensing. The CSMA/CA channel access technique is inefficient due to the poor fairness under high traffic loads and large energy consumption due to channel sensing. To overcome these problems, MAC protocols with a combination of different channel access techniques are developed. Some of the key energy efficient MAC protocols are described briefly in the following.

Duty Cycle MAC Protocol:

In a duty cycling based MAC protocol, sensor nodes operate a duty-cycle to reduce energy consumption, spending most of their time in an idle/sleep mode [81]. When a node wishes to establish a transmission link to a receiver, it will either send a short request packet to the receiver and await a reply; or wait until the receiver is ready to receive a packet if the node has knowledge of the scheduling of the receiver node. If the receiver is ready to receive a data packet, then an acknowledgement (ACK) packet will be sent as a reply and the transmission link is established. Otherwise, the transmitter will repeatedly transmit the request message until either an ACK is received or it exhausts the maximum number of attempts. This strategy eliminates the continuous channel sensing by the sensor nodes. Sensor nodes stay in an idle/sleep mode between transmissions to avoid excess energy consumption.

Wake-up Approach:

The wake-up approach develops this strategy further in [82]. The sensor nodes are equipped with an extra antenna to receive an ultrasound beacon. A node will only wake-up if an ultrasound signal is received. It requires less energy to stay in receive mode for ultrasound at a frequency of 40 kHz than in the 2.4 GHz radio frequency band. The measurement for this study shows a 40% reduction in energy consumption staying in using ultrasound receiving mode than in 2.4 GHz receiving mode. This approach can be further extended to a directional MAC protocol where a beacon can be transmitted to different directions, only awaking a limited number of nodes at a time.

A priority controlled protocol is described in [61] and [62] for personal health care WSN applications. Packets are categorised in terms of priorities, in which periodic data will be transmitted using a slotted TDMA based technique and urgent data packets will be transmitted with a contention based CSMA/CA technique. A beacon is transmitted at the beginning of each timeframe which contains all the required information about time slots, and the start and end period for each node for the periodic data transmission using the slotted TDMA technique. If a node has an urgent data packet to transmit, the node generates a request to transmit data without any delay. If more than one node has urgent data to be transmitted, they will contend for the channel with the CSMA/CA technique. Nodes will remain in a sleep mode to reduce energy consumption and wakeup only when receiving a beacon, when its transmit timeframe is reached, or when an urgent data packet needs to be transmitted. This reduces the channel sensing required by the CSMA/CA technique while allowing packets to be transmitted periodically without collision. The authors have also provided an analysis on the energy consumption for this protocol.

3.4.4 MAC Protocols with Power Control

In [83], a power control mechanism is proposed for directional to directional communications, where transmitter and receiver beamform towards each other to utilise maximum gain to reduce the required transmission power. Upon receiving the RTS from the transmitter, the receiver beamform the antenna to maximise the gain towards the transmitter using the AoA. Note that the transmit power of the RTS has to be at maximum power in case of the antenna pointing at other directions. The transmitter re-adjusts the antenna pattern upon receiving the CTS with the AoA to maximise the gain and to reduce the transmission power for the data packet transmission. However, in a mobile network, the transmitter might send the RTS packet without beamforming towards the receiver correctly causing failure and unnecessary delay.

A beacon base power control mechanism is proposed in [84], where a beacon is transmitted by the receiver periodically (every 465 μs) while receiving the data packet. The transmitting node will enter receiving mode to listen to the beacon for adjusting the transmit power before changing back to transmit mode. This allows the transmitting node to adjust its transmit power dynamically during data packet transmission. This is useful to overcome hidden node problem or new interference during the transmission, but at the expense of increased latency and energy consumption.

In [85], a power control scheme using the control packets is proposed. The CTS packet from the receiver includes a suggested transmit power for the transmitter. However, the values for these power levels are implementation dependent. The approach presented here might achieve an energy efficient MAC for sensor nodes, but only realistic settings of the power level show meaningful results with regards to energy consumption. The energy consumption results presented in this thesis are derived from power level adopted from real devices (i.e. MICAz), where only 3 power levels are allowed. It is also worth noting that although this power control scheme can help reduce the transmit power of the data packet, the physical carrier sensing continues to be the highest energy consumed aspect of the CSMA based protocol.

While most studies focused on how to reduce the transmit power of the data packet, [86] proposed a power control scheme for the receiver, where the ACK packets from the receiver is adjusted to reduce the packet collisions caused by ACK packets.

3.5 Directional Medium Access Control

3.5.1 Overview

Directional antennas provide a number of advantages over omni-directional antennas in WSNs. By focusing energy in the intended direction, directional antennas can increase the potential for longer transmission and reception range, and spatial reuse for the same amount of power. Increased spatial reuse and longer ranges translate into higher sensor network capacity by utilising simultaneous transmissions and fewer relay hops. Furthermore, since the antenna is focused on a smaller area, the chances of interference are reduced; with some adaptive directional antennas, the steering of nulls can allow the suppression of unnecessary interference at the receiver. Replacing omni-directional antennas by directional antennas in WSNs is not by itself sufficient to exploit the offered potential. The directional antenna needs to be appropriately controlled by the MAC protocol. For adaptive systems, such control includes pointing the steerable directional antennas in the correct direction at the correct time for transmission and reception, controlling the transmit power of the packets in accordance with the antenna gain, nulling the adaptive antenna at the interferers, etc. The benefits of directional antennas are listed as follows:

Lower Interference – A directional antenna can concentrate its transmission power in a specific direction. If a receiver is equipped with a directional antenna, less interference will be received from other directions. The narrower the beamwidth of the antenna pattern, the more shielding the node has from interference.

Improved Spatial Reuse – Compared to omni-directional antennas, directional antennas allow for simultaneous communication within the transmission range on the same frequency channel. The capacity of spatial reuse depends on the number of directional antennas, the beamwidth of the antenna pattern and the capability of the MAC protocol to utilise this.

Extended Transmission Range – By focusing the power in a certain direction, a directional antenna acquires a high antenna gain than an omni-directional antenna, which leads to a longer transmission range given the same transmission power.

Reduced Transmission Power – To maintain a successful communication link, the minimum transmission power is inversely proportional to the product of the antenna gains of the transmitter and the receiver. Since directional antennas have higher antenna gains than omni-directional antennas, the use of directional antennas results in a reduced transmission power requirement given the same propagation distance.

3.5.2 Directional Antenna Constraints on MAC Protocol Design

Directional WSNs have a number of features that distinguish them from traditional WSNs; the most apparent differences being the unique antenna directivity, the antenna radiation pattern and antenna gain. These characteristics must be taken into consideration when designing MAC protocols for directional WSNs. This section highlights the constraints that directional antennas place on MAC protocol design, and identifies the desirable characteristics.

Deafness – While directional antennas enable spatial reuse, deafness has been identified to be a major challenge, especially in scenarios where the receiver has only one directional antenna. Due to the directionality of the antenna, devices can fail to communicate with another device because the antenna of the receiving node is pointing in a different direction. This can cause the sender to assume the channel is idle whilst the receiver is communicating with another device. This problem must be carefully addressed for protocols such as a directional CSMA/CA protocol. Figure 3.9 illustrates how deafness can affect WSNs. Consider the scenario in Figure 3.9 (left), N2 is communicating with N1, while N3 attempts to communicate with N1. As N1 is deaf to N3, N3 will assume there is a collision and will enter a backoff state before retransmitting. A number of retransmissions might occur before N1 and N2 terminate their communication, causing unnecessary energy consumption and overhead in communication. Furthermore, if exponential backoff is introduced, multiple backoffs might cause unnecessary delay.

Queue Blocking – Queue blocking refers to data packets within a queue that cannot be transmitted due to blocking from packets in the front of the queue. This occurs with a First-In-First-Out (FIFO) queuing system, especially in scenarios such as multi-hop, mesh, or in wireless networks with directional antennas. FIFO in omni-directional antenna systems would not suffer this problem as no nodes can transmit if the channel is busy. However in directional antenna systems, multiple transmissions can occur due to the benefit of spatial reuse. If the packet at the top of the queue of N3 is destined for N1, but the next few packets are destined for N2, the first packet will block all subsequent packets even if N2 is at idle. This would not just cause unnecessary delay and limiting the network capacity, but also has reduced the benefit of spatial reuse.

Channel Capture – Channel capture can occur due to deafness. If N2 completes communication with N1, then N2 will choose the shortest backoff interval (minimum contention window). If N3 is in the exponential backoff phase, it is likely that N2 will transmit a new packet first, as the backoff counter for N2 is shorter than N3. When N3 finishes its backoff, N2 will be communicating with N1 again, and N3 will enter an even longer backoff, causing channel capture. This could cause N3 to drop multiple packets after a number of retransmissions until N2's queue is empty or N3 is fortunate enough to gain access to the medium before N2.

New Interferer – The use of directional antennas enables the potential of spatial reuse and the benefit of range extension, but it also causes a new exposed nodes problem. Consider a directional to directional communication with reference to Figure 3.9 (right), while N2 is communicating with N1, N1 will also be exposed to N4 due to the extended range. When packets are being transmitted to N1, N4 will become a strong interferer.

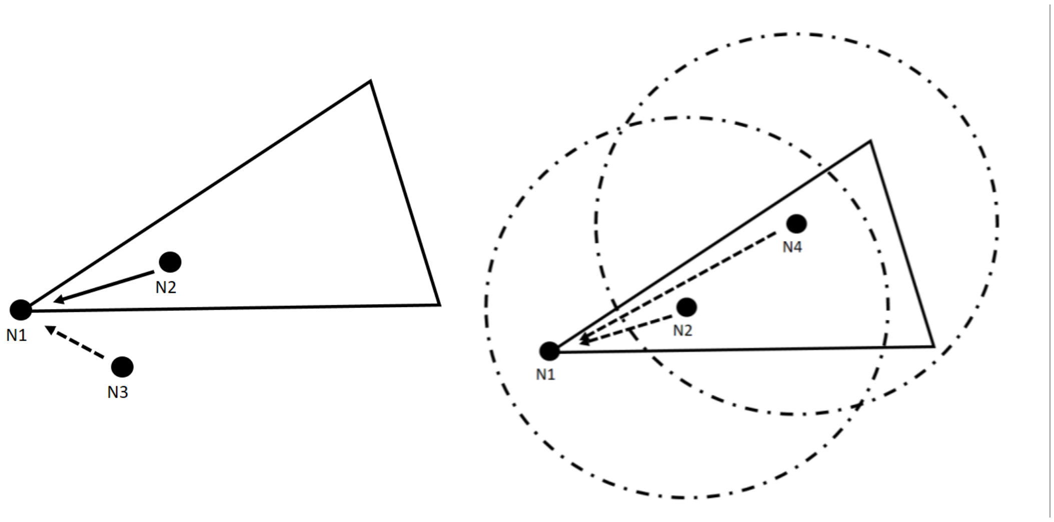

Figure 3.9. The new deafness problem (left) and the new interferer problem (right) for directional MAC protocols.

3.5.3 Desirable Features of a Directional MAC Protocol

Low Complexity – It is desirable to keep the processing and hardware requirements to a minimum in any computational system by minimising the complexity of the algorithm and design. If the complexity and requirements of the MAC protocol can be reduced then the sensor node can be much smaller, operate much faster, consume less power, and be more reliable. The use of directional antennas needs to be carefully considered. Although Section 3.6 highlights that more directional antennas at each node can lead to better spatial reuse and throughput performance, the number of directional antennas to be equipped should be reasonable to reduce the physical size of the sensor node and the energy consumption of the sensor node. Furthermore, there are physical limits and spatial separation requirements for certain types of device, having an extensive MIMO array on a small or mobile device is very unlikely.

Sustainability – The ability for a WSN to have a long lifetime is an important feature for a WSN. Since wireless sensor nodes are operated mostly from batteries, it is important for the MAC protocol to be designed for a low sensor node energy requirement. In scenarios where sensor nodes are deployed in inaccessible or hazardous locations, the MAC protocol needs to be able to prolong the network lifetime as maintenance or battery replacement is not a feasible option. In a WSN where directional antennas are employed, the directionality and the gain of the directional antenna should be fully harnessed to achieve an energy efficient MAC protocol.

Mobility Support – For MAC protocols designed for WSNs with only omni-directional antennas, the position and the mobility of the sensor nodes are less important than in MAC protocols with directional antennas. Since the directional antenna should be pointing towards the desired direction; if the sensor node is moving while the communication link is being established, the sensor node might leave the directional antenna's sector during the transmission, under which circumstances the communication link is dropped without providing useful throughput. A well designed MAC protocol should be able to handle both stationary and mobile sensor nodes, providing desirable performance. The ability of the scheme to continue to provide service in the presence of mobile nodes at different velocities is also an important factor.

3.6 Directional MAC Protocols Review

3.6.1 Overview

The MAC protocols outlined so far have considered only one level of omni-directional channel access. MAC protocols for wireless systems have been subjected to extensive research and development since the 1970's and numerous examples have been described in the literature. Yet, significant shortcomings of WSNs remain, especially with respect to fundamental capacity limitations [87]. The recent trend towards convergence to directional communication from omni-directional communication has resulted in a number of MAC protocols designed to support a much wider range of applications and channel access techniques. As stated in Section 3.4, it appears that no single channel access technique is able to provide both high channel utilisation and low energy consumption for WSNs. It is therefore common to employ a hybrid MAC protocol which combines several channel access techniques.

MAC protocols for traditional WSNs were designed with omni-directional communication systems in mind, in which modifications are needed in applying directional antennas.

3.6.2 Directional MAC Protocols

An example approach is the simple directional CSMA/CA protocol proposed in [88], which divides the network spatially to enhance spatial reuse. All sensor nodes are equipped with three fixed directional antennas and that physical space is divided into three equal sectors. Sensor nodes are by default in an idle listening state if the packet queue is empty. Each antenna operates independently and will listen to the channel for incoming transmissions. If a sensor node has a data packet to transmit, it will perform channel sensing with all antennas, followed by a RTS message transmitted in all directions by using all of the directional antennas. Upon receiving the RTS message, the receiver will note the angle of arrival (AOA) of the RTS message and reply with a CTS message using the most suitable directional antenna. If the receiver has only one available antenna (sector), it will still respond to the sender to enhance spatial reuse. Other sensor nodes overhearing the RTS message will also note the AOA and update the NAV of the antenna pointing in that direction, whist the other directional antennas remain available.

In [89], a simple directional MAC (DMAC) approach for contention based protocols such as CSMA/CA has been proposed. Sensor nodes perform channel sensing in all directions and estimate the AOA of each communication they overhear. When a sensor node has a packet to send, it will beamform its steerable directional antenna towards the designated receiver using the AOA information previously acquired. All communication is performed directionally in the DMAC protocol, although omni-directional communication is also supported, for instance if a sensor has no AOA information prior to a packet transmission. In this protocol, it is shown that the throughput performance can be improved by directional-to-directional communication, where both senders and receivers operate in a directional only mode. However, all sensor nodes need to be equipped with steerable directional antennas and AOA information is assumed to be available at each node. Analysis of the throughput performance for the directional CSMA/CA protocol is described in [90].

A single channel directional MAC (DMAC) protocol that attempts to harness the potential of directional antennas is described in [91] by Ramanathan *et al*. The protocol has been developed based on the IEEE 802.11 CSMA/CA/DCF protocol, with modifications to exploit the potential of directional antennas. Switched or steered directional antennas can be employed, replacing the traditional omni-directional antenna. Similar to the CSMA/CA/DCF protocol, sensor nodes perform channel sensing prior to RTS transmission. However, if a sensor node has a data packet to transmit, directional channel sensing will be performed instead of omni-directional channel sensing. Antennas are switched or steered towards the intended receiver with the aid of the Global Positioning System (GPS) for the purpose of channel sensing, packet transmission and reception. A dynamic NAV strategy similar to [88] is also employed, aiming to remove the unnecessary backoff and delay constraints caused by control packets in other unintended directions.

The concept of using directional antennas for contention based protocols was developed further by [85]. The fundamental nature of their scheme is very similar to the one described in [89], but a modified power control strategy is considered. In

[89], the transmit power of sensor nodes are not adjusted, only the direction of the antennas is considered. The scheme proposed by [85] considers the application of the directional antennas with a power control scheme. If a sensor node has a data packet to transmit, it sends a directional RTS to the receiver. The receiver replies with a CTS message where the required power of the CTS is calculated by measuring the interference around the node. A predicted value is then sent to the source node in the CTS message. The source node then transmits the data packet with an adjusted transmit power using the predicted value in the CTS message.

A nulling directional CSMA/CA protocol designed to maximise SINR is described in [92], proposed by Fahmy and Todd. In this selective nulling scheme, an additional Cooperative Nulling (CN) packet is added following a RTS/CTS message exchange. The idea is for all sensor nodes that received the CTS message to transmit a short CN packet, including the source node. Once the receiver node receives the CN packets, it will attempt to beamform towards the desired transmitter, maximise the SINR and null the interferers. The beamforming is only performed by the receiver during data and ACK packet transmission, and all transmissions are operated with omni-directional antenna. The proposed scheme allows random channel access without synchronisation and without requiring sensor nodes to know the location of the receiver. However, it is shown that transmission power control might not be suitable for this protocol.

An example of a multi-channel MAC protocol designed to improve the throughput performance by reducing the hidden terminal and deafness problems is the Dual Sensing Directional MAC (DSDMAC) protocol, proposed by Abdulah *et al* [93]. The scheme incorporates two separate channels, a data channel and a control channel. The data channel allows sensor nodes to transmit all packets including the control packets and data packets, where the sensor nodes follow the handshaking mechanism of the IEEE 802.11 CSMA/CA/DCF protocol. Directional transmissions are performed on the data channel to exploit the potential of spatial reuse. On the other hand, a control channel is used where nodes can transmit a busy-tone beacon in all unused directions during an on-going transmission. Each sensor node is equipped with multiple directional antennas to allow simultaneous transmission for both data packets and busy-tone beacons. The beacon notifies neighbouring sensor nodes about the busy nodes and avoids deafness and the hidden terminal problem. However, this scheme does not support simultaneous reception despite multiple directional antennas being equipped at each sensor node.

The concept of having multiple channels to improve throughput performance was further developed by Wang *et al* [94]. A Cooperative Multi-Channel Directional MAC (CMDMAC) protocol is proposed in which sensor nodes are able to transmit control packets such as RTS and CTS packets with a control channel, and transmit data packets on another channel. A total of four data channels are available within this scheme. When a user has a packet to send, it performs channel sensing on the control channel followed by transmission of an omni-directional RTS packet. If the request is successful, an omni-directional CTS will be returned to the sender. Judging on the Direction of Arrival (DoA) of the RTS packet, the CTS packet will include the expected data channel and antenna sector information. The neighbouring nodes that overhear the control messages may know which data channel and antenna sector is reserved. The neighbouring nodes will also update their directional network allocation vector (DNAV) according to the overheard control messages. Upon a successful control message handshake, the sender will transmit the data packet on the reserved data channel and antenna sector. If the trailer transmission is successful, the packet will experience much lower interference (if any) due to the assigned data channel. Challenges such as deafness and hidden terminal problems can also be significantly reduced by this scheme as the control packets are transmitted omni-directionally.

The Slotted Aloha protocol with the use of directional antennas for WSNs was first proposed in [95], by Hung and Yum. The directional Slotted Aloha protocol attempts to benefit from spatial reuse by equipping sensor nodes with multiple directional antennas. When a packet is ready to transmit, the sensor node will choose a suitable directional antenna, depending on the destination of the receiver, and transmit the packet at the beginning of the next timeslot. The theoretical results have shown that the throughput gain could be as large as the number of directional antennas used by the sensor nodes.

Fung *et al* have further developed a simple scheduled access directional Slotted Aloha MAC protocol in [96]. A single hub topology is considered, in which all sensor nodes and the hub node are equipped with multiple sectorised directional antennas. The scheme is based on the traditional Slotted Aloha protocol, where nodes are allowed to transmit data packets at the beginning of the next timeslot. However, instead of transmitting the data with an omni-directional antenna, nodes transmit the data packets with the directional antenna pointing at the receiver. In this scheme, physical space is divided into M sectors, where M is the number of directional antennas. Sensor nodes will have knowledge of the position of the hub node, or the sector where the hub node is located. Sensor nodes will then only transmit their data packets using that sectorised directional antenna, reducing interference in other directions.

The IEEE 802.11n standard [97] marks the beginning of a new generation of 802.11 standards, being the first 802.11 standard amendment to introduce Multiple-In Multiple-Out (MIMO) transmission. The MIMO technique, along with other innovations allow 802.11n to provide higher data rates, throughput and longer range compared to the 802.11a/b/g standards. The use of multiple antennas makes transmission more robust through spatial reuse. The improved performance usually leads to increased power consumption. Recent measurement studies have shown that 802.11n is power hungry and could deplete battery quickly if it operates continuously in the constantly awake mode (CAM) [98, 99]. This is obviously a significant concern for mobile device. The 802.11n standard also includes the power save mode (PSM), which tries to save power by turning off the network interface whenever possible [100]. Although different vendors may adopt variant implementations, normally, all antennas are turned off after a predetermined idle period and turned on again when packets arrive [101].

Wi-Fi IEEE 802.11ac is the improvement of IEEE 802.11n. IEEE 802.11ac improves the performance of big data streaming, multiple devices connection, and further the transmission distance [102]. IEEE 802.11ac achieves better performance by increasing the bandwidth and increasing the scale of MIMO, while IEEE 802.11n has up to four spatial streams with up to 40 MHz bandwidth, IEEE 802.11ac has up to eight spatial streams with up to 160 MHz bandwidth [103]. IEEE 802.11ac has great similarity to 802.11n in terms of channel access, with an extension of Request-To-Send/Clear-To-Send (RTS/CTS) to help avoid collisions with users operating on slightly different channels. IEEE 802.11ac extends the 802.11n channel access mechanism with control messages handshaking and backoff occur on a single 20-MHz primary channel, and Clear Channel Assessment (CCA) used for the remaining 20-MHz sub-channels immediately before transmitting on them. First, when a 802.11ac device sends an RTS, the transmitter has to verify the 80-MHz channel is clear in its vicinity, then the RTS is normally sent in a 802.11a Physical Protocol Data Unit (PPDU) format. The basic RTS transmission, which is 20 MHz wide, is replicated another three times to fill the 80 MHz (or another seven times to fill 160 MHz). Then every nearby device, regardless of whether it is an 802.11a/n/ac device, receives an RTS that the device can understand on its primary channel. And every device that hears the RTS set the channel to busy. Secondly, before the device addressed by the replicated RTS responds with a CTS, the receiver checks to see if anyone is transmitting near itself, on its primary channel or on any other 20 MHz. If a portion of the bandwidth is in use nearby, the receiver responds with a CTS only on the available 20 MHz sub-channels. The available sub-channels is defined as the sub-channels on which the transmitter is allowed to transmit, such as a 20, 40, or 80 MHz (but not 60 MHz) transmission [103].

IEEE 802.11ad is a standard aimed at leveraging the large 2.16 GHz-wide channels available in the 60 GHz frequency band. One of the advantages of 60 GHz communications is that the frequency resource is abundant but free. However, the signal in this frequency band degrades more significantly than that in the traditional 2.4 GHz or 5 GHz band, especially when passing through walls or over distances [104]. IEEE 802.11ad uses directional beamforming to mitigate the high propagation loss inherent to the high frequencies used, and thanks to constructive multipath it has been shown to achieve indoor ranges up to 50 m [105]. Compared with the legacy IEEE 802.11 Distributed Coordination Function (DCF), the IEEE 802.11ad DCF has significant distinct features due to the use of directional antennas and a hybrid access mechanism. All the wireless nodes cannot simultaneously listen to hub due to directional communications. Hence the area around a hub is divided into multiple sectors, and nodes in each sector can compete to access channel only during the allocated time for that particular sector. The CSMA/CA operation in a sector is suspended when either the TDMA based channel access is instantiated or when the hub is busy facilitating other sectors.

The channel access time under IEEE 802.11ad is divided into beacon intervals (BIs), and each BI mainly consists of four parts: (i) beacon transmission interval (BTI), where hub transmits one or more beacon frames via different beams in a sector sweep manner; (ii) association BF training (A-BFT); (iii) announcement transmission interval (ATI), used to exchange the management information such as the transmission allocations with the DTI; and (iv) data transfer interval (DTI), consisting of contention-based access periods (CBAPs) and service periods (SPs) employing CSMA/CA and TDMA [106].

3.7 Summary and Discussion

This chapter has provided an overview of fundamental multiple access techniques, described the methods and issues associated with MAC protocol design for WSN with directional antennas. A comprehensive literature review on contention-based random access MAC protocols has also been provided, specifically looking at those able to support directional antennas.

Directional random access contention-based protocols have been selected for investigation in this chapter, primarily due to their appropriateness to supporting dynamic traffic and the flexibility they provide for scalability. A number of standard multiple access techniques are available for directional WSNs and they have been described and related to key attributes of an effective MAC protocol. It has been identified that random access techniques such as CSMA/CA are necessary in achieving a high channel utilisation for dynamic traffic, but that continuous sensing and exponential backoff have resulted in high energy consumption, delay performance and a lack of fairness. Hybrid protocols adapting multiple channel access can improve the situation by reducing the channel sensing duration and the backoff duration, providing a more rapid and effective method for packet transmission, but they are limited by the fundamental spatial reuse capability. Contention-based random access strategies for directional WSNs are analysed in

Chapter 5, providing a thorough understanding of their fundamental performance and appropriateness to different channel and network conditions.

Numerous hybrid MAC schemes have been discussed in the literature for the directional WSN scenarios combined with several multiple access techniques, aiming to achieve both high channel utilisation and good energy performance. The majority of these schemes combine random access with the TDMA technique, primarily with an initial channel access technique such as CSMA/CA for slot reservation backed up by a TDMA duty cycle for data transmission. A second group of techniques combine contention-based random access with FDMA assignment. These schemes have been subject to less widespread development but are attractive due to their multi-channel contention-free data transmission nature.

It has been highlighted that whilst these schemes are able to offer significant improvement in channel utilisation and throughput performance, they remain constrained by limitations in energy consumption, fairness, delay, and the ratio of antenna pattern overlap. Most of the directional MAC schemes described in the literature are agnostic to whether the transceiver uses switched or steered beams. This is done by using the transmission direction as the unifying abstraction. In a steered beam or adaptive array system, the beam is steered or beamformed as close to the specific direction as possible, with no considerable side or back lobes. On the other hand, the receiver of a switched beam system in some studies assumed multiple transceivers with a large number of main beams with narrow beamwidth per transceiver. The reason behind this assumption is with only few wide-beam antennas, the front to back lobe ratio is low, thus causing significant overlap to antennas at other transceivers. Each transceiver consists of multiple narrow-beam antennas and with the lowest angular separation from the specific directional is selected for communication each time, the front to back lobe ratio will be high [107]. In a directional antenna system, it is critical to determine the appropriate antenna gain correctly because: 1) in some scenarios the transmitter and receiver may be using different antennas, and 2) the direction the antennas are pointing, regardless of whether they are steered or switched, may not be the exact direction of the corresponding receiver or transmitter.

This makes the design and implementation of the directional MAC protocols simpler and portable from other antenna system, but impractical under realistic scenarios. In most studies, either GPS is available for each sensor node, or the location of the receiver is known for the antenna selection. However, these MAC schemes fail to account for obstacles or sensor node mobility during the antenna selection stage, assuming that the direction of the receiver is always the best option for the antenna beams. It is clear that an alternative approach for directional channel access is key in achieving an improvement with respect to the different performance metrics under dynamic traffic loads. Significant advances in directional MAC protocol design are introduced and described in Chapters 5 and 6.

Chapter 4 - Modelling and Performance Evaluation

Content

This chapter describes the techniques and simulation software that are used to model the Wireless Sensor Network (WSN) scenarios and evaluate the network performance. The performance metrics are also explained in this chapter.

The performance of wireless communication systems can be measured by practical experiments with real hardware devices. However, simulation models can describe the behaviour of the system to predict its performance. By virtually representing a real system using simulation tools, the system performance can be predicted without the high cost of practical experimentation.

4.1 Simulation Software

With the advancement of wireless communication systems, modelling different applications and scenarios analytically are getting more complex. As a result, computer simulations provide an alternative less complicated solution. The software tools used in this study are Matlab and the Riverbed Modeler [108], which is previously known as OPNET. Matlab is used for mathematical analysis and estimation, along with processing simulation results from Riverbed Modeler. Riverbed Modeler is used for the simulation of the MAC protocols and the directional antennas.

4.1.1 Riverbed Modeler

Riverbed Modeler provides a virtual environment for modelling and analysing wired and wireless network systems in order to provide predictions of different performance metrics. This allows researchers to develop advance protocols and evaluate their enhanced performance. The simulator provides several different levels for network modelling including project, node, process, and pipeline stage models. The project model presents the network layer of the WSN, in which the architecture and topology can be defined with specific node altitudes, latitudes, longitudes and the distance between the nodes. The trajectory for mobile nodes can also be defined at the project model level. An example of a mobile network is shown in Figure 4.1.

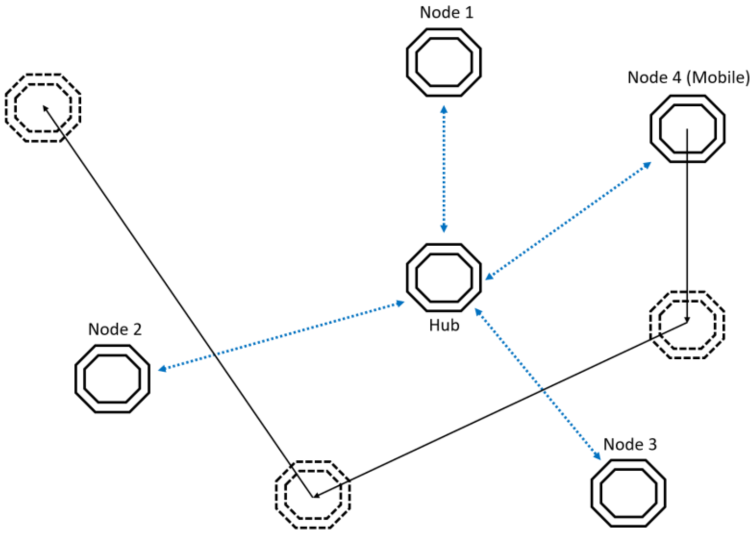

Figure 4.1. Riverbed Modeler project model design example, where the blue lines indicate the communication link and the black line represents the trajectory of the mobile node.

Each of the nodes in Figure 4.1 has a corresponding node model that implements the functional structure of the nodes, consisting of the processor, transceivers, packet generator, the antenna patterns, etc. The packet streams connecting the functional blocks define the flow of packets from one block to another. Figure 4.2 shows an example of the node model for the hub node in Figure 4.1 with four directional antennas. The node model defines the functionality at the modular level, in this case it is comprised of a packet generator (Gen), a processing block or the MAC block (MAC), four sets of transmitters (tx), receivers (rx) and antenna patterns (Ant) as it represents four sets of transceivers of the node.

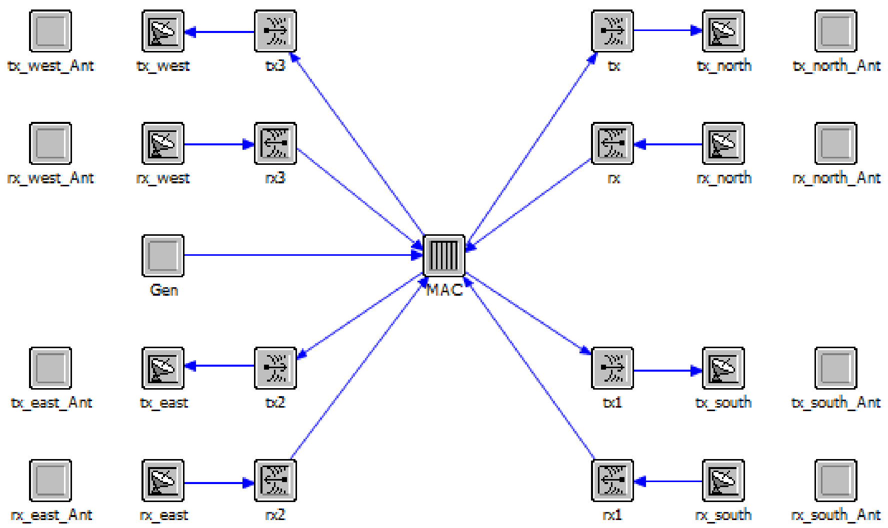

Figure 4.2. Riverbed Modeler node model design example.

The process model allows a finite state machine (FSM) to be used to model a detailed network protocol and algorithm implementation. On the other hand, the different pipeline stages can model all aspects of wireless communication including radio propagation, antenna models, interference, transmission power, etc. Details on the simulation methodologies of the WSNs considered in this thesis are described in the following sections.

4.1.1.1 Network Topology and Scenario

An example scenario of a star-based WSN in which 50 sensor nodes transmit data towards a hub node is depicted in Figure 4.3. Here, a WSN is deployed to collect and relay data to a single sink node (also known as the hub node), which is located at the centre of the network with a grid size of 100 m x 100 m. The sensor nodes are randomly deployed within the network grid with their coordinates generated using a pseudorandom number generator. The sensor nodes are deployed at the same altitude, so the network topologies are two-dimensional. All simulations reported in this thesis are using a single 250 kHz channel in the 2.4 GHz ISM frequency band [37], with the assumption of Line-of-Sight (LoS) communication.

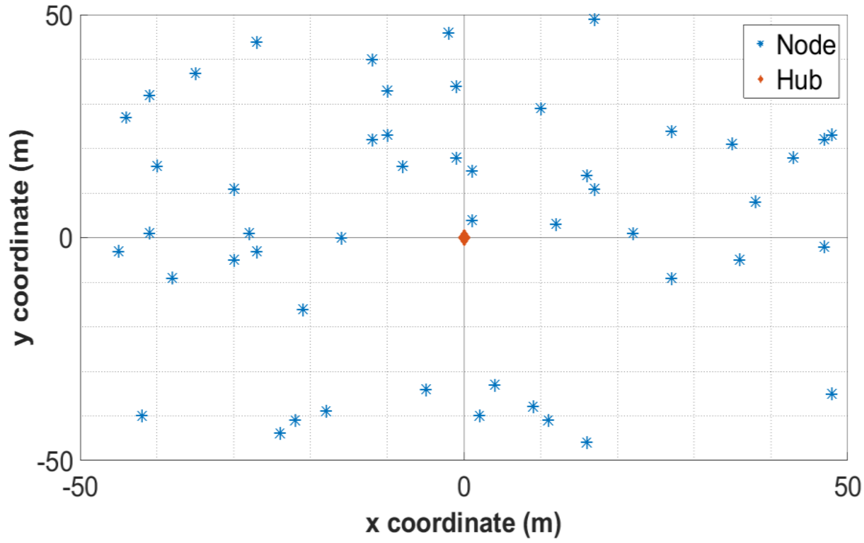

Figure 4.3. Wireless sensor network (WSN) simulation scenario.

4.1.1.2 Link Model

A realistic value of the noise floor for the wireless receivers is -120 dBW. It is calculated using the following equation:

$$P_{TBN} = 10\ log_{10}\ (k\ T\ B) \tag{4.1}$$

where P_{TBN} is the thermal background noise power, k is the Boltzmann constant ($1.381 \times 10^{-23}\ JK^{-1}$), T is the noise temperature in K (290 K) and B is the bandwidth in Hz (250 kHz). The Noise Figure is the ratio between the actual noise output of a receiver and the ideal noise output based on the ambient temperature. The Noise Figure is assumed to be 1 in this thesis, which means there is no difference between actual noise output and thermal noise corresponding to the ambient temperature (290K), as the performance evaluation is orientated around the interference effects from other transmission rather than the effects of noise. It is worth noting that only thermal background noise is implemented for the simulations in this thesis.

4.1.1.3 Propagation Model

Free space propagation has been considered in this thesis as an illustrative example, where its model may also be derived from the Friis transmission equation. The received power of the signal P_r can be described by the following equation:

$$P_r = P_t\ G_t\ G_r (\frac{\lambda}{4\ \pi\ d})^2 \tag{4.2}$$

where $P_t$is the transmission power of the signal, G_t and G_r are the antenna gain of the transmitting and receiving antenna respectively, d is the propagation distance between the antenna pair.

The free space path loss ($FSPL$) in decibels (dB) can be expressed as:

$$FSPL(dB) = 10\ log_{10}\left(\left(\frac{4\ \pi\ d\ f_c}{c}\right)^2\right)$$

$$= 20\ log_{10}\left(\frac{4\ \pi\ d\ f_c}{c}\right) \tag{4.3}$$

where f_c is the carrier frequency of the signal (ie 2.4 GHz in this thesis), and c is the speed of light.

4.1.1.4 Traffic Model

Load is defined as the level of demand placed on a channel, expressed either as data bits per second or as a fraction of the useful channel capacity in Erlangs. Channel utilisation refers to the level of channel usage, which is attained by placing an equivalent traffic load on the channel. For instance, 50% channel utilisation is achieved by placing a channel load 50% or 0.5 Erlang. Since this is relative to the raw physical transmission rate over the channel and errors are neglected, this is a fair approximation of the channel capacity. The Poisson distribution is used to model the packet arrival process at the sensor nodes, as the inter-arrival time of the packets fits an exponential distribution. The Poisson distribution is a traditional model for generating data traffic, commonly used in MAC protocol performance evaluation. Considering natural occurring events, the traffic of the WSN can be modelled with the Poisson distribution characterised by the exponentially distributed packet inter-arrival time. The Poisson distribution is a very attractive for use in queuing theory due to its memoryless aspect, where there is no dependency with successive packets and without any correlation between sensor nodes. All results presented in this thesis are obtained with the Poisson distribution model as it is supported by standard queuing theory, analytically tractable, and there are many naturally occurring phenomena that fit a Poisson process in which WSNs may be deployed in. The overall network activity level of the source is set by the mean time between packet generations and the inter-arrival time. Individual packets are generated with an exponentially distributed inter-arrival time at each node. Each sensor node can be set to generate data packets at a specific rate using different offered load, generally less than the channel capacity. A model, in which each sensor node contributes an equal amount of traffic to the channel, has been developed in Riverbed Modeler with the mean inter-arrival time derived from the overall traffic offered load given by:

$$T_{int} = \frac{L}{R} \cdot \frac{n}{G} \tag{4.4}$$

where L is the data packet size, R is the data rate, n is the number of sensor nodes within the network, and G is the overall network traffic offered load.

The total traffic load then represents the sum of these individual offered loads, in which 1 Erlang represent 100% traffic load in a single channel, single antenna system.

4.2 Performance Metrics

An important aspect of WSN modelling is performance evaluation which is subject to the appropriate choice of the metrics. The performance metrics used to analyse the simulation results presented in this thesis are described in this section.

4.2.1 Throughput

The throughput performance of a network can be considered as the time portion of the total time the medium successfully transfers information between stations. Throughput performance is particularly relevant to data transmission as it measures the rate at which a system successfully delivers the offered data. Throughput can be defined as the proportion of the channel capacity that is effectively used for useful data throughput, usually one of the most used criteria in MAC protocol performance evaluation. It is usually expressed as a function of traffic offered load in this thesis. Load here refers to the level of traffic placed on a channel, expressed either as a fraction of the useful throughput over the overall channel capacity of the channel in the units of Erlangs, or as the number of useful data bits received.

4.2.2 Signal-to-Interference-and-Noise Ratio

The signal-to-interference-plus-noise ratio (SINR) is fundamental for determining the quality of the link performance. It is the ratio between the power of the received signal of interest and the sum of the received powers from all sources including the noise power. SINR accounts for the radio propagation effects such as path loss and interference. The SINR at a given receiver can be expressed as follows:

$$SINR = \frac{P_{tx}\, G(\theta_t)_{tx}\, G(\theta_A)_{rx}\, P_L}{\sum_{i=1}^{N} P_{tx}^{i}\, G(\theta_t)_{tx}^{i}\, G(\theta_A)_{rx}\, P_L + P_{TBN}} \tag{4.6}$$

where the received power of the signal of interest is P_{tx}, $G(\theta_t)_{tx}$ and $G(\theta_A)_{rx}$ are the antenna gains of the transmitter and receiver of interest, based on the angle of transmission θ_t and angle of arrival (AoA) θ_A, P_L is the propagation loss between the transmitter and the receiver, N is the number of interfering transmitters, ie. all transmitters that are transmitting using the same frequency at the same time, $P_{tx}^{i}\ and\ G_{tx}^{i}$ represent the received power and the antenna gain of the interfering transmitters, and P_{TBN} is the receiver background noise power calculated in Equation 4.1. The receiver gain of the interferers depends on the orientation of the directional antenna at the hub. The orientation limits whether a sensor node is considered an interferer as introduced later in the thesis. The antenna gain of the receiver depends on the directional antenna used and the angle of arrival (AoA). A look-up table is used to ascertain the bit error rate (BER) corresponding to the SINR level. This BER value is used to determine whether each individual bit within the packet are received in error, based on the generation of uniformly distributed random numbers between zero and one, assuming uncoded binary phase shift keying (BPSK) modulation. The calculation of the SINR will become more complex in a multipath environment. Multipath is the reception of multiple copies of the same transmission, each arriving from a different propagation paths, which combined in a constructive or destructive manner that distorts the received signal. This can be caused by reflections off the ground or other obstacles.

4.2.3 Transmission Efficiency

There is a trade-off between the link performance and the transmission efficiency of the network. Since failed transmission leads to wasted transmission energy, energy efficiency is directly affected by the transmission efficiency of the network. For instance, achieving high throughput may be at the expense of the energy efficiency and network lifetime. One of the major limitations of WSNs, specifically with battery powered sensor nodes, is the energy efficiency of the sensor nodes. These sensor nodes are usually powered by batteries with a limited lifespan, after which recharging or replacing the batteries can be challenging especially with applications such as wildlife monitoring, military, and security surveillance as well as environmental monitoring. Therefore, energy efficiency is necessary. An energy consumption calculation model is developed in this thesis to evaluate the energy efficiency of the DMAC protocols. The transmission efficiency can be expressed as:

$$TE = \frac{D_{rx}}{D_{tx}} \, x \; 100\% \tag{4.7}$$

where D_{rx} is the successful data reception (in bits) and D_{tx} is the total data transmission (in bits) by the sensor nodes during the measured period.

4.2.4 Fairness

In wireless communication, fairness is an attribute to resource sharing or allocation. An unfair system may result in an inefficient use of resources and poorer overall performance. Some MAC protocols are designed to offer equal channel access probability to all sensor nodes in the network, mostly with scheduled access techniques, whereas some other protocols are designed to focus on other Quality of Service (QoS) requirements. Network fairness can be defined as the ability to offer equitable channel access to all users. While network throughput is a performance metric used to provide an overall channel utilisation of the WSN, fairness is a key metric for ensuring fair data packet collection across the whole network. In order to measure the fairness of a network, Jain's fairness index [109] has been used due to its ability to represent the variability of the set of measurements, such as the individual throughput of each sensor nodes. In some scenarios where each sensor node might have a different offered load or, Jain's index might not be suitable for measuring fairness. However, since the offered load is shared by all sensor nodes in this thesis, Jain's fairness index is an appropriate approach for fairness measurement.

Ideally, when all sensor nodes have equal channel access probability, the fairness index should be equal to 1. Jain's fairness index can be expressed as:

$$FI = \frac{\left(\sum_{i=1}^{n} S_i \right)^2}{n \sum_{i=1}^{n} {S_i}^2} \tag{4.8}$$

where n is the number of sensor nodes in the network, and S_i is the individual throughput of each sensor node.

4.2.5 End-to-End Delay

The end-to-end delay of a packet transmission is the time taken for a packet to be successfully received at the destination node at the other end of the communication link from the time it was generated at the source. It consists of a number of components including the queuing delay prior to transmission, scheduling delay from the MAC protocol, packet transmission duration, and radio propagation delay. The mitigation of end-to-end delay of a packet transmission to some degree is relevant as any reduction in delay of packet transmission is indicative of a more efficient MAC protocol, especially for WSN applications where real-time data transmission is essential. These time sensitive data transmission applications include aircraft safety monitoring and personal health monitoring. The mean value of end-to-end delay is commonly used as a performance metric and as such results presented in this thesis show the mean end-to-end delay performance as a function of the channel offered load. The end-to-end delay shows the time required for a packet to be received successfully, providing specific information on the achievable performance in terms of latency. Since the traffic type in this thesis is not as delay sensitive as other traffic, such as real time traffic, using mean delay is adequate as a performance metric in this thesis.

4.3 Directional Antenna Patterns

An important aspect of a WSN using directional antennas, is the antenna pattern. The directional antenna patterns used to analyse the performance of the directional MAC protocols are presented in this section.

In this thesis, four directional antennas are chosen as a reasonably practical number to illustrate the performance of a multi-antenna hub. Fewer antennas could result in packet loss due to the gaps between the antennas with the realistic directional antennas used in this thesis. However, if the number of antennas were significantly increased, the issue of antenna overlap may become a significant problem. To thoroughly investigate the impact antenna patterns have on MAC performance, an ideal sector antenna with a beamwidth of 90^o and two realistic antenna patterns Antenna 1 (Ant 1) and Antenna 2 (Ant 2) from [110] were used to provide simulation results for the comparison and validation.

4.3.1 Idealised Sector Antenna

In the literature, simplifying assumptions such as the use of idealised antennas were made. An idealised antenna refers to a distinct directional antenna beam with a constant antenna gain across the beam and no side and back lobes. These ideal antenna patterns mean that there will be no overlap with adjacent beams. Figure 4.4 shows the beam pattern of an ideal sector directional antenna.

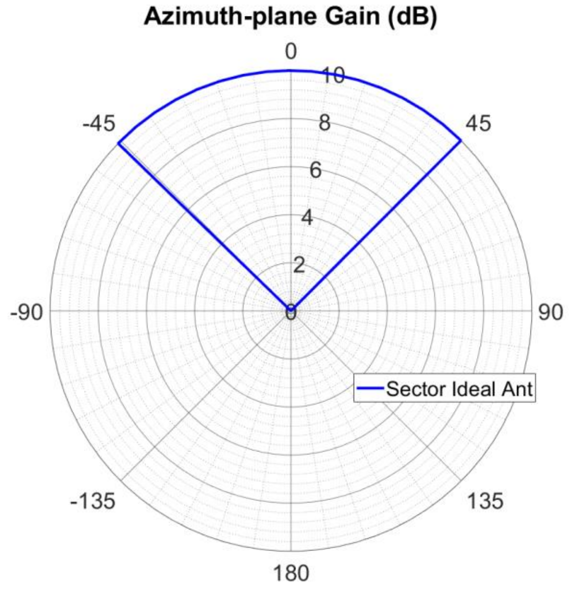

Figure 4.4. An example polar plot of an ideal sector directional antenna with a beamwidth of 90^o.

4.3.2 Realistic Antennas

Antenna 1 (Ant 1) is a 3-element Yagi antenna with a maximum gain of 9.37 dBi and Antenna 2 (Ant 2) is an ESPAR antenna with a maximum gain of 10.83 dBi. Figure 4.5 shows the measurement of the realistic directional antenna patterns. In order for a packet to be received successfully, the signal-to-interference ratio (SIR) limit must be considered. The angle θ_{A1} and θ_{A2} denote the angle over which each antenna can successfully receive packets, and the edge of these angles are the SIR limits. These are described in detail in chapter 5.

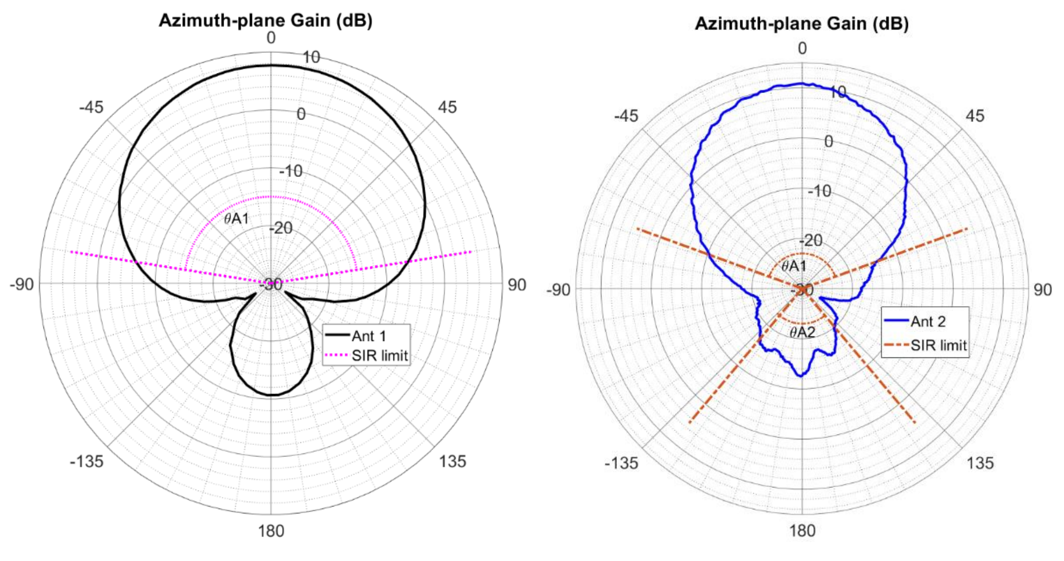

Figure 4.5: Polar plot of the antenna pattern of Ant 1 and Ant 2.

4.4 Summary

This chapter described the simulation tool used for wireless network system modelling and the performance evaluation of the MAC protocols proposed in this thesis. A simple WSN scenario, that involves sensor nodes collecting and transmitting data back to a single hub station, is used as the basis for the detailed simulation model. The key metrics used to assess the performance of the simulated protocols are the throughput, energy efficiency, latency, and network fairness. The standard Aloha and CSMA protocols are used for baseline comparison in the simulation which will be discussed in the rest of this thesis.

Chapter 5 Directional Hub Aloha Protocol

Contents

5.1 Introduction

This chapter proposes a novel Directional Hub Pure Aloha (DH-Aloha) protocol for single-hop centralised communication and provides a practical implementation of it, which was published in [18]. DH-Aloha extends the most basic contention-based protocol, the Pure Aloha protocol, by exploiting multiple directional antennas with realistic antenna patterns to improve the network throughput with low end-to-end delay.

A number of medium access control (MAC) protocols have been developed for various wireless sensor network (WSN) applications. Since the majority of traditional MAC protocols were designed for wireless sensor nodes equipped with an omni-directional antenna, they do not exploit directional antennas [111]. One major limitation of traditional MAC protocols, such as the Pure Aloha and Slotted Aloha protocols, is the limited network throughput they can deliver. In recent years, researchers have been exploiting the use of directional antennas in the development of MAC protocols to achieve high link performance by improving spatial reuse [88, 93, 95]. Specifically, extensive research on directional MAC (DMAC) protocols have been focusing on the contention-based operation [14, 15, 21, 92, 112-114] that aims to provide significant improvements in Quality of Service (QoS) on performance metrics such as network throughput for WSNs. The combination of directional antennas and contention-based protocols can provide a higher throughput performance for WSNs with low end-to-end delay. There are a number of variants of contention-based protocols, differing in their provision and strategy.

There are generally two types of directional contention-based protocols that have been detailed in Chapter 3:

- Directional Aloha
- Directional CSMA

The proposed DH-Aloha scheme can be categorised as one of the Directional Aloha protocols. In the DH-Aloha scheme, the principle for the hub is to determine an optimum antenna for the transmission to each sensor node based on its past experience. DH-Aloha assigns a hub antenna to each sensor node within the network and this is updated after each transmission based on the received signal strength of the data packet. Although researchers have found that throughput can benefit from enhanced spatial reuse; their results are based upon a number of impractical assumptions, such as an idealised antenna pattern without back-lobes or side-lobes, unlimited node power consumption, or sensor nodes with multiple directional antennas which can operate at multiple frequencies.

In the proposed DH-Aloha protocol, multiple practical directional antennas are introduced to account for the practicality issues. Since realistic directional antenna patterns are employed, the neighbouring patterns are always overlapping to guarantee the full coverage of the hub. The overlapping antenna patterns could result in collision and packet loss due to the fact that the packets from sensor nodes in the overlapping region may be received by two or more antennas, thereby resulting in an increased probability of collision. Simulation models have been developed using Riverbed Medelor (previously known as OPNET) [108] with suitable modifications to include overlapping antenna patterns and possible lost transmissions in the implementation of the DH-Aloha protocol.

Section 5.2 describes the random access technique, focusing on the Pure Aloha scheme in detail. The novel DH-Aloha protocol is presented in Section 5.3. In addition, the throughput performance of DH-Aloha with multiple hub antennas is evaluated based on a combination of graphical and mathematical analysis. The model is applied to investigate the impacts of various realistic limitations of antenna patterns, such as side lobes, back lobes, and overlapping antenna patterns, on the throughput performance. A detailed evaluation of DH-Aloha is presented in Section 5.4, where the simulation results are compared with those from the analytical models with different directional antenna patterns to validate the simulation models. Section 5.5 concludes this chapter.

5.2 Random Access -Pure Aloha Scheme

The Aloha schemes were briefly introduced in Chapter 3 and are referred to Section 3.2.6, and the performance of this random access technique in terms of throughput, stability, and scalability is investigated in this section. The Aloha schemes are some good examples of simple MAC protocols that employ a blind transmission strategy. The behaviours of the Aloha protocols allow users to transmit their data as soon as a data packet is ready for transmission, which is important for certain categories of WSNs with limited resources such as memory and power. Medium access that does not require pre-coordination would result in packet collision if more than one packet are received during the same period of time. One of the assumptions in the modelling of the performance of these schemes is that all fully or partially colliding packets are considered as loss.

5.2.1 Theoretical Throughput Analysis with Infinite Number of Nodes

The theoretical throughput analysis of the Aloha schemes relies on a number of simplified assumptions but does provide a useful upper bound of the throughput capability. It is assumed as described in [115] that:

- The number of transmitting sensor nodes tends to infinity.
- Packets are generated at each sensor node according to a Poisson distribution.
- All data packets are of the same length and transmission power, hence the same transmission duration and the same received power at the receiver.
- All packet losses are the result of full or partial collisions.
- At any instant in time, each sensor node has no more than one packet ready for transmission, hence no queuing at the packet queue.

The theoretical throughput for Pure and Slotted Aloha are given in Equation (5.1) and Equation (5.2) [42]. Figure 5.1 shows the theoretical throughput as a function of the overall channel traffic offered load.

The analytical throughput model of Pure Aloha is given by:

$$S = G\, e^{-2\,G} \tag{5.1}$$

where S denotes the network throughput in Erlangs and G is the overall channel traffic offered load.

The analytical throughput model of Slotted Aloha is given by:

$$S = G\, e^{-\,G} \tag{5.2}$$

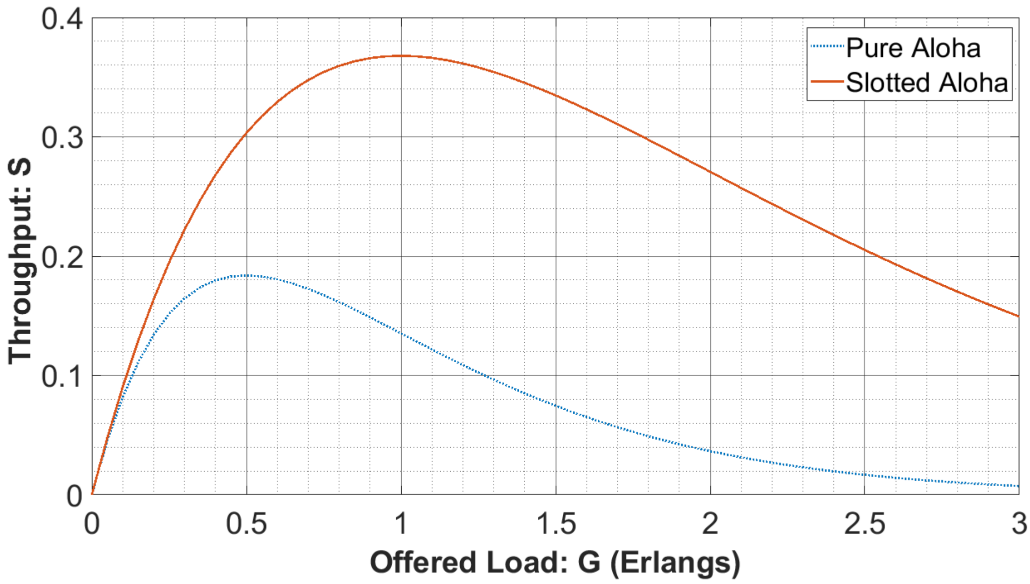

Figure 5.1. Theoretical throughput performance of Pure and Slotted Aloha.

The maximum throughput of Pure Aloha is ~18.4% of the total channel capacity (0.184 Erlang) at an overall traffic offered load of 50% (0.5 Erlang). The Slotted Aloha has a higher maximum throughput of ~36.8% (0.368 Erlang) at a maximum overall traffic offered load of 100% (1 Erlang), where the channel traffic level is equal to the maximum channel capacity. For both Aloha schemes, when the demand traffic load of the channel exceeds the maximum throughput capacity, the packet collision rate increases. As a result, the network throughput capability is reduced, in which the network enters an unstable state with minimal useful throughput.

5.2.2 Theoretical Throughput Analysis with Finite Number of Nodes

For practical deployments, it is essential to provide a mathematic analysis for these protocols with a finite number of nodes. In this section, the theoretical throughput analysis for Pure and Slotted Aloha with a finite number of nodes is presented. Here, a number of n nodes are considered, where each transmits a packet with the same probability p based on Poisson distribution and the overall network traffic offered load G. The assumptions for this analytical model are identical to those in Section 5.2.1, except that the number of transmitting nodes are limited.

The probability of a packet arriving at each node from its upper layer is related to the overall network traffic offered load by:

$$p = \frac{1}{n} G \tag{5.3}$$

The probability of k transmissions from a number of n nodes within a single data packet transmission duration can be expressed by the binomial distribution as:

$$p(k\ in\ n) = \frac{n!}{k!\,(n-k)!}\, p^k\, (1-p)^{n-k} \tag{5.4}$$

Therefore, the probability of a successful transmission/only one transmission from a number of n nodes is:

$$p(1\ in\ n) = \frac{n!}{1!\,(n-1)!}\, p^1\, (1-p)^{n-1}$$

$$= np\,(1-p)^{n-1} \tag{5.5}$$

The probability of no collision during this transmission is:

$$p(0\ in\ (n-1)) = \frac{(n-1)!}{0!\,((n-1)-0)!}\, p^0\, (1-p)^{(n-1)-0}$$

$$= (1-p)^{n-1} \tag{5.6}$$

The theoretical throughput S for Pure and Slotted Aloha in a finite number of sensor node system are given in Equation 5.7 and Equation 5.8.

$$S = p(1\ in\ n)\, p(0\ in\ (n-1))$$

$$= n\,p\,(1-p)^{n-1}\,(1-p)^{n-1}$$

$$= n\,p\,(1-p)^{2(n-1)} \tag{5.7}$$

$$S = p(1\ in\ n)$$

$$= n\,p\,(1-p)^{(n-1)} \tag{5.8}$$

Figure 5.2 and Figure 5.3 shows the theoretical throughput of the finite node analytical model of Pure Aloha and Slotted Aloha with respect to different number of nodes. The standard infinite node analytical model is also included for comparison. The throughout with a finite number of sensor nodes is higher than the infinite node case as expected. When the number of node increases, the throughout tends to match the infinite node case.

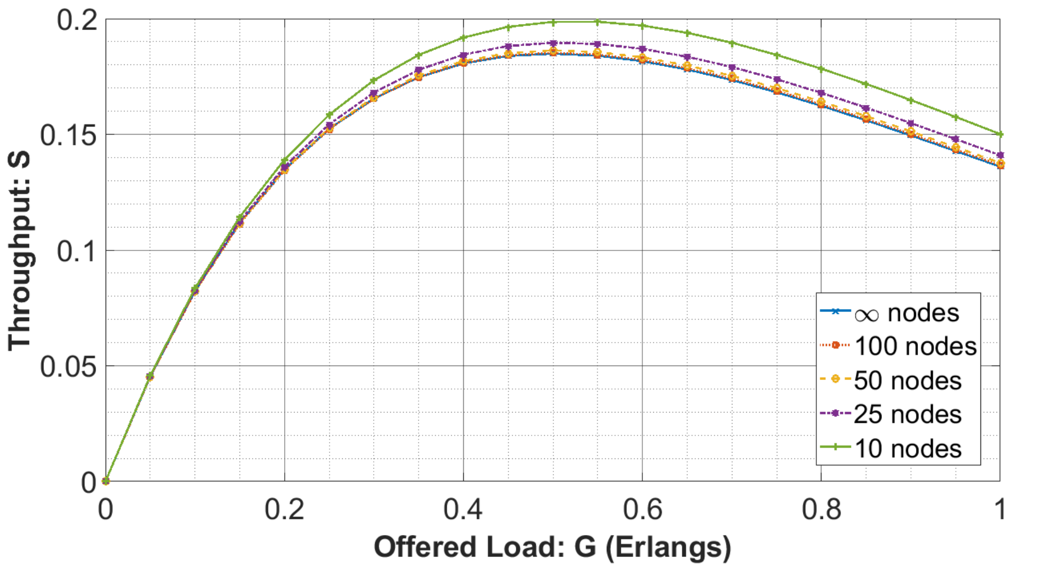

Figure 5.2. Pure Aloha throughput with different number of nodes from Equation 5.1 and Equation 5.7.

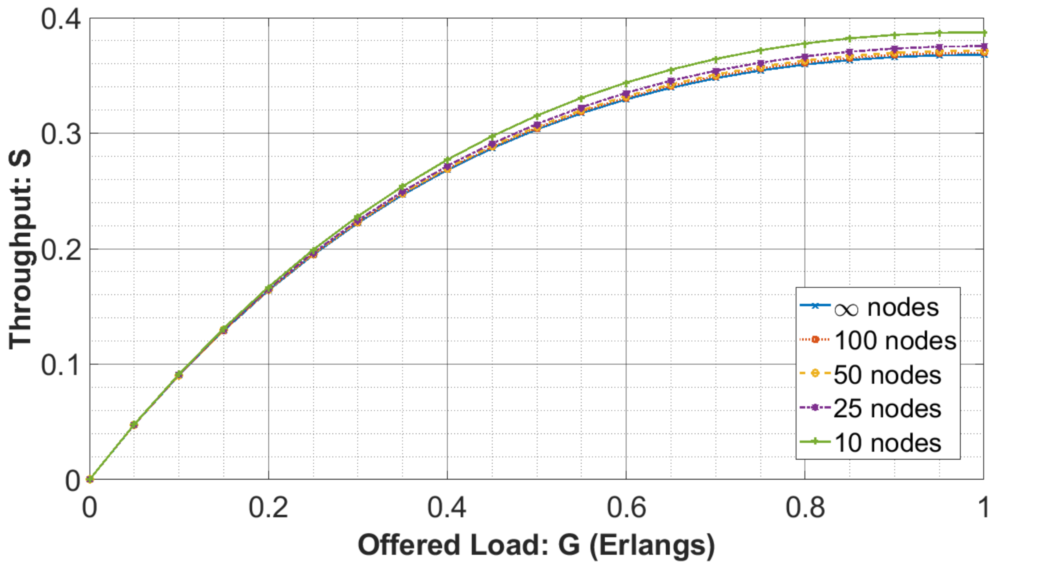

Figure 5.3. Slotted Aloha throughput with different number of nodes from Equation 5.2 and Equation 5.8.

5.2.3 Simulation Model of Aloha Protocols

A simulation model of Aloha schemes has been developed using the Riverbed Modeler with the simulation parameters given in table 5.1. Each node has the same average inter-arrival time i expressed as:

$$i = \frac{L\ .\ n}{G\ .\ d} \tag{5.9}$$

where L is the packet length, n is the number of users and d is the data rate of the channel.

Table 5.1. Simulation parameters for Aloha Protocols.

Parameters	Values
Physical Layer	IEEE 802.15.4
Frequency Band	2.4 GHz
Number of nodes	30, 50, 100, 200
Channel Data Rate	250 kbps
Packet Length	1024 bits
Transmit Power	0.01 W
Transmission Distance	50 m

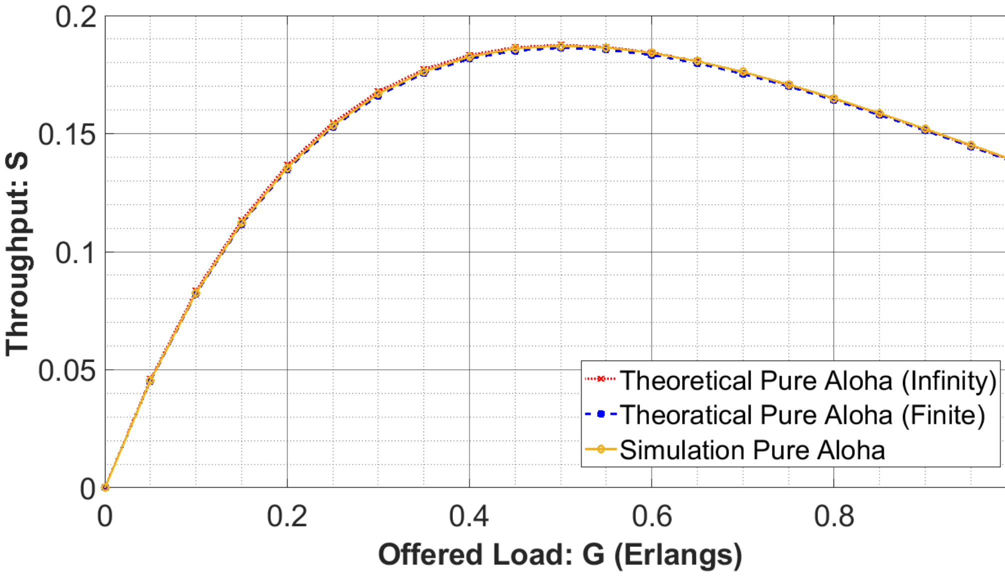

Figure 5.4. Pure Aloha throughput 50 sensor nodes.

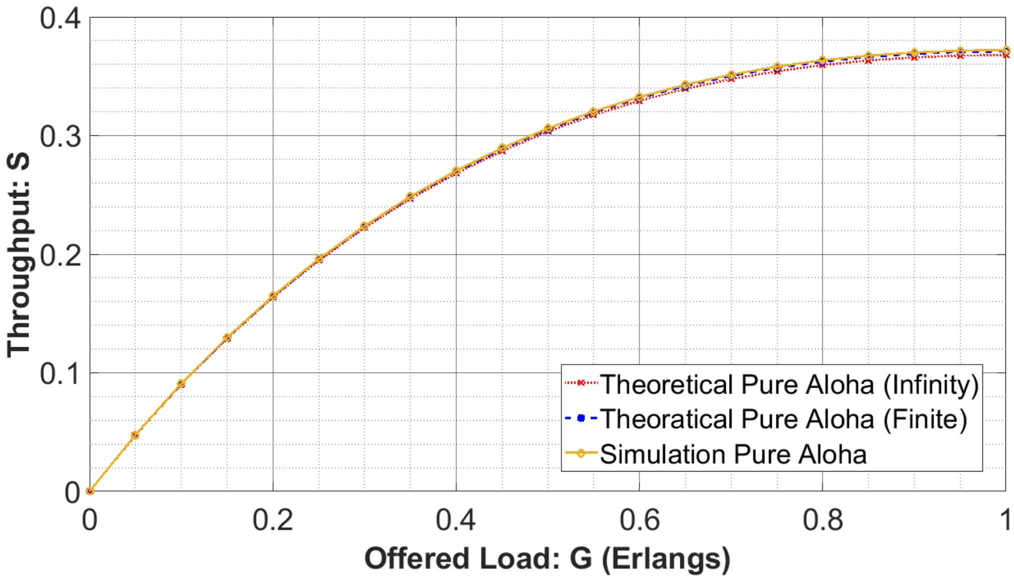

Figure 5.5. Slotted Aloha throughput 50 sensor nodes.

From Figure 5.4 to 5.5, it can be seen that the simulation results agree very well with the analytical results in both cases, which validates the accuracy of both the analytical and simulation models. Furthermore, the analytical and simulation results provide an insight into the behaviours of the Aloha protocols using signal channel transmission. It shows that random access protocols are limited by low throughput capability, but they can provide rapid channel access with less packets build up in the queue and benefits to devices with limited local memory [42]. Therefore, a large number of MAC protocols described in the literature employ contention-based medium access.

5.3 Directional Hub Aloha Protocol

As stated in Chapter 3, a lot of research has been carried out by using Multi-Input-Multi-Out (MIMO) along with directional antennas to improve the performance of WSNs. The directional hub Aloha MAC (DH-Aloha) protocol operates a centralised WSN with multiple directional antennas at the hub node. The advantage of the directional antenna is to provide spatial reuse and additional antenna gain, which improves the QoS of random access techniques.

5.3.1 DH-Aloha MAC Description

The DH-Aloha-MAC protocol is an extended version of the Pure Aloha protocol by replacing an omni-directional antenna with multiple directional antennas at the hub node. In DH-Aloha, a directional hub comprises of $\boldsymbol{M}$ directional antennas with the same beam width but different orientations so that the $\boldsymbol{M}$ antennas cover the sensor nodes in all the directions. Each directional antenna's sector covers $\frac{\mathbf{1}}{\boldsymbol{M}}$ of the physical space. In this protocol, the sensor node's behaviour is the same as in the Pure Aloha protocol. The nodes are only allowed to send one packet at a given time, and the generated packets are queued First-In-First-Out (FIFO) with the packet at the head of the queue being transmitted. In this protocol, all communications are initiated by the sensor nodes. However, if the hub needs to communicate with sensor nodes, and there are no prior communications between them, a random antenna will be selected to communicate with the sensor node. Whenever the hub receives a packet from a node, it may be received by more than one antenna. The directional antenna with the highest signal-to-interference ratio (SIR) is preferred and the data received by the other antennas is discarded. The optimum value is determined by the signal quality of received packet, the higher the signal quality, the higher the optimum value. As we assume that (i) nodes may move; (ii) the propagation environment could change; (iii) obstacles and sources of interference would change over time, the optimum antenna associated with each sensor node is expected to change over time. Figure 5.6 presents the finite state machine (FSM) diagram of the sensor node (a) and hub node (b) of the DH-Aloha protocol.

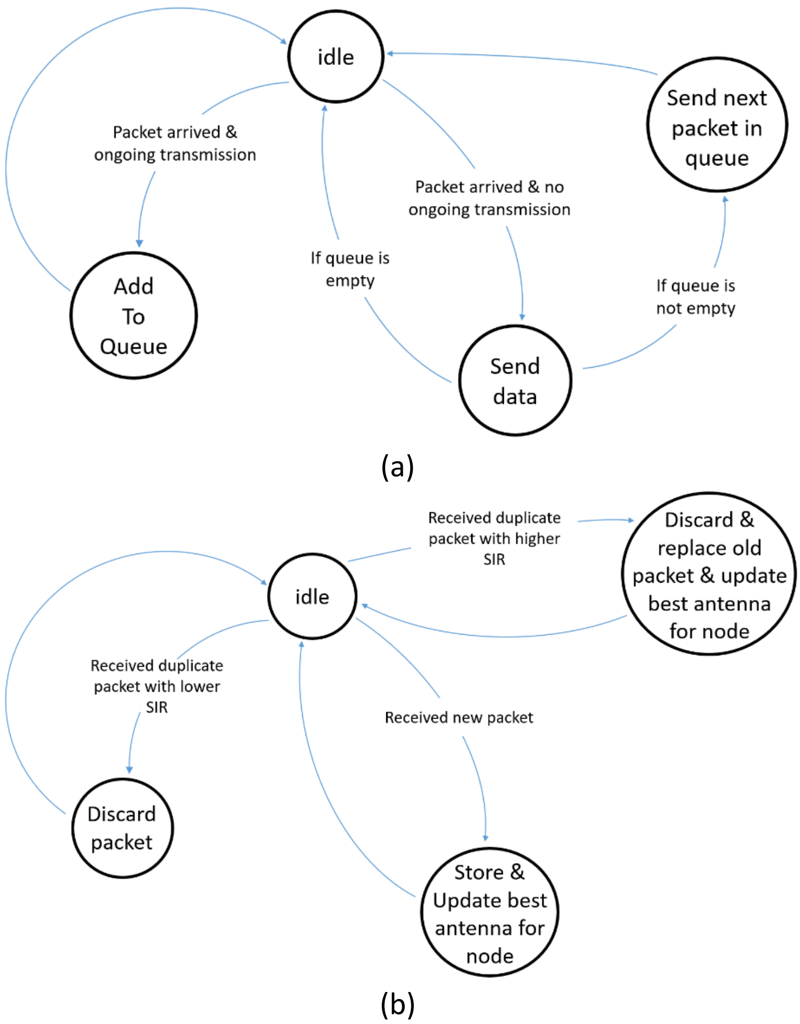

Figure 5.6. DH-Aloha system state diagram (a) sensor node, (b) hub node.

There are three reasons for choosing this approach. Firstly, it increases the potential channel capacity without increasing the complexity of the sensor node by combining the use of multiple directional antennas at the hub with a contention-based protocol. Secondly, no synchronisation is required between the nodes and the hub in order to facilitate the use of directional antennas. Thirdly, no simplified assumption is made in terms of the directional antenna pattern, which enables a more realistic performance evaluation compared to different protocols proposed in the literature review in Chapter 3.

Although this topology is simple, it is a representative of many application scenarios and it can be considered as a one-hop sub-network in a more complicated network scenario, such as a clustered network. Here, we consider the scenario where n sensor nodes gather data and contend for the access to a single frequency channel by means of the Pure Aloha protocol. Packets are transmitted on a best effort basis, without any acknowledgements or retransmissions. If a data packet in a sensor node is ready for transmission, it will be sent immediately unless there is an ongoing transmission. Each node generates packets with an exponentially distributed inter-arrival time, and all nodes have the same mean packet inter-arrival time. No synchronisation is performed between the sensor nodes and the hub.

5.3.2 Theoretical Throughput Analysis

The overall network throughput performance is one of the most common performance attributes used to evaluate a MAC protocol. The results have shown that the mean throughput performance is heavily dependent on the directional antennas applied. As a result, the number of the directional antennas and by extension their antenna patterns must be carefully chosen. In this section, analytical expressions of the network throughput for a directional WSN are derived and demonstrated for the WSN with a specified number of antennas and antenna patterns.

5.3.2.1 Hub Directional Antenna Numbers

In the single omni-directional antenna Pure Aloha case, the theoretical throughput is given by Equation 5.1, with the assumption of a very large number of transmitting nodes. The number of directional antennas (M) is a key feature to the potential enhancement of spatial reuse in a WSN. When M ideal antennas without overlapping antenna beams are used at the hub, the system behaves as if there are M separate Pure Aloha systems given that the sensor nodes can be assumed to be equally distributed between the M antennas. The network traffic offered load to each antenna is $\frac{1}{M}$ of the total load, and the overall throughput (S_{Mno}) is M times as large as that of a single antenna system. Considering the throughput analysis for Pure Aloha in Equation 5.1, the overall network throughput of such a system is therefore given by Equation 5.10, where the total offered load G is shared across M hub antennas, with the overall throughput being multiplied by M as it can be assumed as M separate systems with no antenna overlap. Figure 4.2 in Chapter 4 shows an example pattern of an ideal sector directional antenna and Figure 5.7 shows the theoretical throughput of DH-Aloha with M ideal sector directional antennas and infinite sensor nodes as a function of the network traffic offered load. Figure 5.7 shows that the maximum achievable throughput is heavily dependent on the number of hub antennas.

$$S_{Mno} = M\left(\frac{G}{M}e^{-2\frac{G}{M}}\right) \tag{5.10}$$

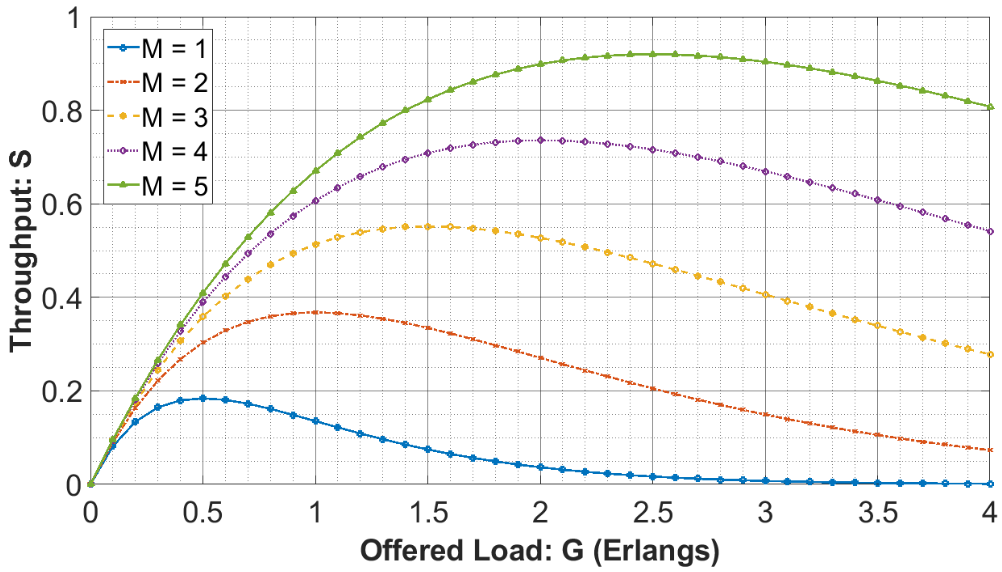

Figure 5.7. The theoretical throughput of DH-Aloha with M ideal antennas with infinite number of nodes.

In order to analyse the throughput performance of the DH-Aloha for practical systems, the analytical expressions for a finite number of sensor nodes can be derived from Equation 5.3 and Equation 5.7 in a one antenna systemas:

$$S_1 = \mathrm{n}\left(\frac{1}{n}\mathrm{G}\right)\left(\left(1-\frac{G}{n}\right)^{2(n-1)}\right) \tag{5.11}$$

where n is the number of sensor nodes within the network.

Equation 5.12 derives the theoretical throughput of the DH-Aloha protocol M antennas are applied at the hub with no overlap from Equation 5.10 and Equation 5.11, in which the network offered load to each antenna is $\frac{1}{M}$ of the total load with n nodes.

$$S_{Mno} = \mathrm{M}\left(\frac{G}{M}\left(1 - \frac{G}{M\,n}\right)^{2(n-1)}\right) \tag{5.12}$$
$$= \left(G\left(1 - \frac{G}{M\,n}\right)^{2(n-1)}\right)$$

Figure 5.8 shows the throughput discrepancy of the DH-Aloha protocol with a finite and infinite number of nodes. The throughput discrepancy here can be defined as the difference between the maximum achievable throughput of DH-Aloha protocol with a finite and infinite number of nodes. It is worth noting that, as the number of sensor node increases, the throughput discrepancy decreases. Although the analytical model for the infinite node case provides a close estimate for a WSN with a large number of nodes, the analytical model for finite nodes can provide a more reliable upper bound throughput estimation for smaller WSNs.

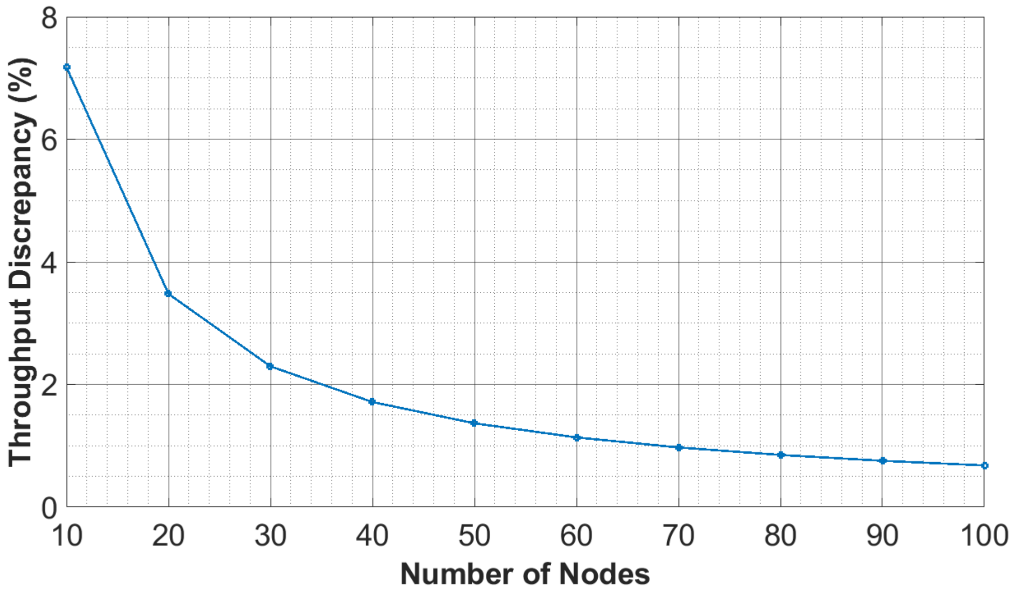

Figure 5.8: The average throughput discrepancy of DH-Aloha throughput analysis with finite sensor node number over throughput analysis with infinite nodes.

5.3.2.2 Antenna Overlap Effect

The throughput analysis in Section 5.3.2.1 provides the maximum potential throughput performance of the DH-Aloha, where each directional antenna is idealised with constant gain across the antenna beam and has no side or back lobes. However, overlap between the antenna patterns occurs in any practical system and the packets from sensor nodes in the overlapping regions may be received by multiple antennas, thereby resulting in a higher probability of collision [18]. Each of the M antenna sectors subtend an angle of:

$$\theta_S = \frac{360}{M} \text{ degrees} \tag{5.13}$$

where θ_S is the sector angle and in any real system, the real antenna will have a coverage angle greater than it.

If the beam width of each antenna is θ_A degrees, which is larger than θ_S to make sure a full coverage (azimuth plane) of sensor nodes, each antenna will see its offered load increased by a factor of r times the case with no overlap, where:

$$r = \frac{\theta_A}{\theta_S} \tag{5.14}$$

Also, a proportion of the packets will be received by more than one antenna, which further reduces the effective throughput by a factor of r. Therefore, the overall throughput with infinite nodes is given by:

$$S_{Mwo} = \frac{M}{r}\left(\frac{G}{M} r e^{-2\frac{G}{M}r}\right) = Ge^{\frac{-2\,G\,r}{M}} \tag{5.15}$$

In order to determine θ_A, the required signal-to-interference ratio (SIR) must be considered. When all the nodes are assumed to have the transmit power, which is adjusted to keep a constant received signal strength at the hub, the packet from the node located in the boresight of one antenna ($\theta = 0^{\text{o}}$) can be interfered by a packet from the sensor node at the angle less than $\frac{\theta_{A0}}{2}$. $\frac{\theta_{A0}}{2}$ is the angle where the antenna gain drops by the amount equal to the required SIR:

$$G(\theta_{A0}/2) = G(0) - SIR \text{ dB} \tag{5.16}$$

where *G(θ)* is the antenna gain at the angle θ from boresight. A node at the sector edge ($\frac{\theta_S}{2}$) can be interfered by nodes at a wider range of angles. Once the angle of the interferer has increased until the gain has fallen from the value at $\frac{\theta_S}{2}$ by an amount equal to the SIR, then its signal is too small to interfere and cause a collision. The value of SIR will depend upon the transmit power of the sender as stated in Equation 4.6 in section 4.2.2. We define this as θ_A so that:

$$G(\theta_A/2) = G(\theta_S/2) - SIR \text{ dB} \tag{5.17}$$

Figure 5.9 shows θ_{A0} and θ_A of Ant 1. In a 4-antenna hub system, the sector angle $\theta_S = 90^o$. If the intended transmitting sensor node is located at the boresight (i.e. at 0^o), sensor nodes transmitting within $\theta_{A0}/2$ (i.e. in this case 70^o) can cause interference to the intended transmission. On the other hand, if the intended transmitting sensor node is located at the sector edge (i.e. 45^o from boresight), sensor nodes transmitting from within $\theta_A/2$ (i.e. in this case 81^o) can cause interference due to the SIR level of the interfering signal. As a result, all sensor nodes located with the sector can suffer interference from sensor nodes transmitting with $\theta_A/2$ with the same transmit power. A suitable power control mechanism can reduce the angle of θ_A, this is further discussed in Chapter 6. Figure 5.10 shows the theoretical throughput of the network throughput as a function of the traffic offered load with a variation of overlap factor r.

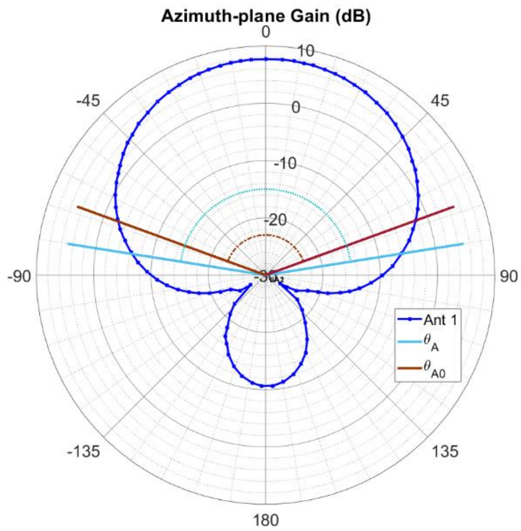

Figure 5.9. Polar plot of Ant 1 with θ_{A0} and θ_A labelled.

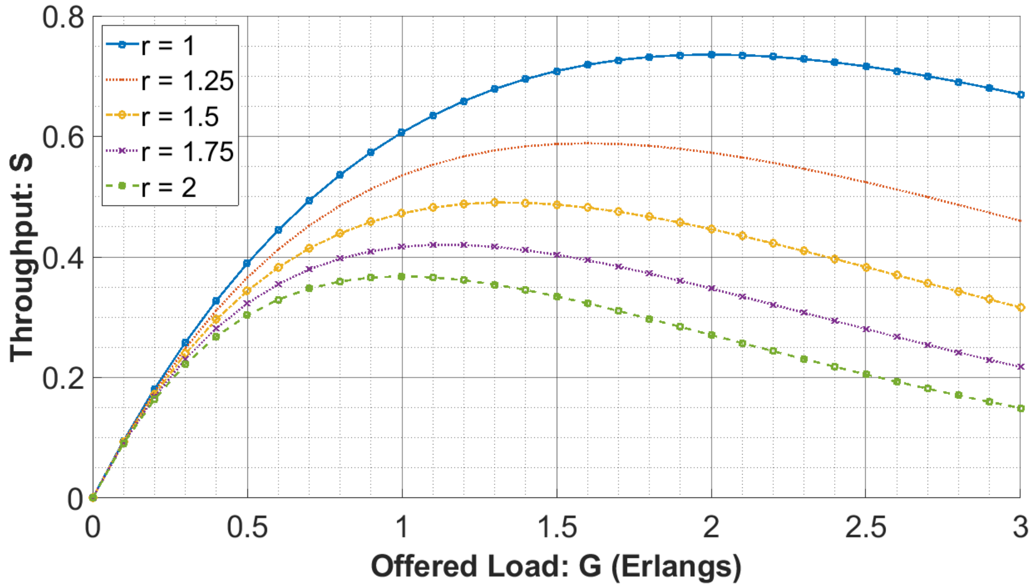

Figure 5.10. The theoretical throughput of DH-Aloha with $M = 4$ antennas and a variation overlap factor r.

Following the same procedure above, the overall throughput performance for the DH-Aloha protocol in a finite node system with $M = 1$ can be derived Equation 5.18, and with M hub antennas in Equation 5.19.

$$S_1 = \left(\mathrm{G\,r}\left(1 - \frac{G\,r}{n}\right)^{2(n-1)}\right) \tag{5.18}$$

Equation 5.19 derives the theoretical throughput of the DH-Aloha protocol. M antennas are applied at the hub as a function of the overlap factor r, in which the network offered load to each antenna is $\frac{1}{M}$ of the total load with n nodes.

$$S_{Mwo} = \frac{M}{r}\left(\frac{G\,r}{M}\left(1 - \frac{G\,r}{M\,n}\right)^{2(n-1)}\right) = G\,\left(1 - \frac{G\,r}{M\,n}\right)^{2(n-1)} \tag{5.19}$$

Figure 5.11 presents the throughput discrepancy between the throughput with finite nodes and that with infinite nodes as a function of traffic offered load and overlap factor for different number of nodes. It shows that the throughput discrepancy between the two models is low when the number of nodes is high, but as the number of nodes decreases, the throughput discrepancy increases rapidly. The throughput performance prediction becomes less accurate as the number of nodes reduces, since the packet queue builds up due to on-going transmissions and less transmitting nodes are available in the network. By considering the wide range of potential WSN applications, it is important to have both analytical models to provide reliable throughput performance prediction at different network topology scenarios. The analysis of the throughput discrepancy between the finite node and infinite node analysis show the importance of having an accurate and realistic throughput performance prediction for practical system, especially for system will a small number of nodes.

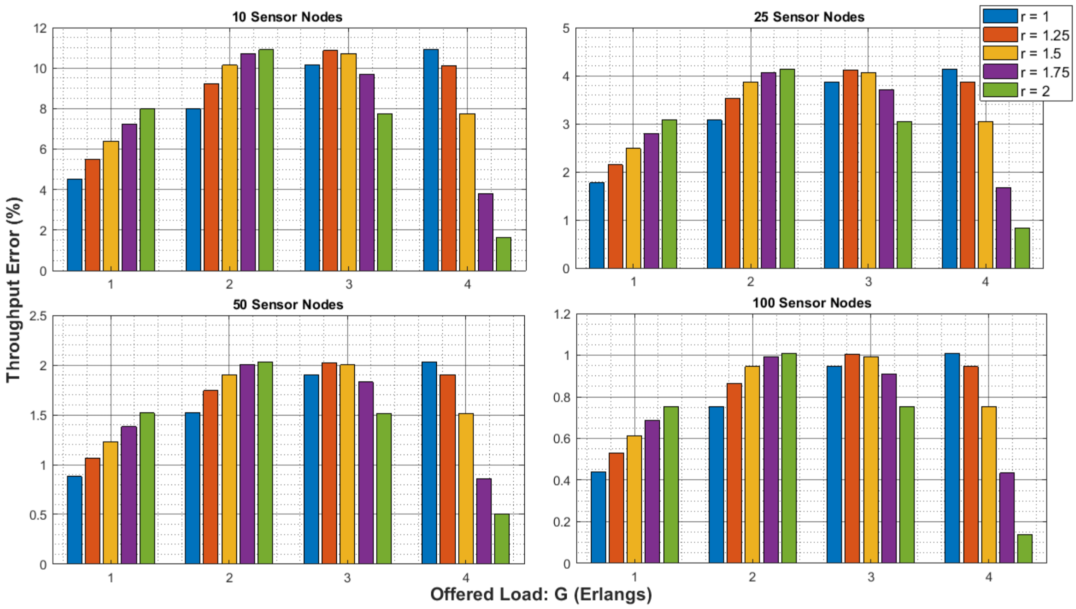

Figure 5.11: Throughput discrepancy of finite node scenarios between analytical models for infinite node and finite node.

5.4 Performance Evaluation and Model Validation of DH-Aloha

5.4.1 Overview

In the previous section, the throughput performance of the proposed DH-Aloha scheme was analysed for various combinations of the number of directional antennas M, number of sensor nodes n, overlap factor r, and offered load G. However, the overlap factor r was not calculated from the antenna pattern; thus, the actual antenna pattern is still not included in the models. This section presents the simulation results of the DH-Aloha scheme by incorporating multiple directional antennas with realistic antenna patterns. The overlap factor r is calculated based on the simulated antenna pattern using CST microwave studio [116]. Simulation results are compared with the analytical analysis obtained in the previous sections to validate the simulation models. Table 5.2 gives the parameters used in the analytical evaluation and the simulation models.

Table 5.2. Parameters for DH-Aloha protocol analytical and simulation models.

Parameters	Values
Physical Layer	IEEE 802.15.4
Frequency Band	2.4 GHz
Number of nodes (n)	50
Network Traffic Offered Load (G)	0.1 – 3.0 Erlangs
Channel Data Rate	250 kbps
Packet Length	1024 bits
Transmit Power (P_{tx})	0.01 W
Network Size	100 x 100 m^2

5.4.2 Effect of Antenna Pattern Overlap

Riverbed Modeler was used to develop 10 different simulation scenarios of different random topologies. Chapter 6 shows the throughput performance with error bars labelled, given the small deviation between the results, 10 iterations was deemed to be sufficient. In all the simulation models, each sensor node has an isotropic antenna with the transmission power of 0.01 W and gain of 0 dBi. The hub was equipped with four fixed directional antennas oriented toward north, east, south, and west (N, E, S, W). The Riverbed Modeler models are simulated with three different antenna patterns to emulate the analytical throughput model described in Section 5.3.

In this implementation, the simulation parameters are the same as those of IEEE 802.15.4 compliant systems, which operate in the 2.4 GHz band, with a packet length of 1024 bits, use the Poisson traffic model, and exclude the complexities of spread-spectrum. The purpose of this set of results is to assess the performance of the DH-Aloha protocol using realistic directional antenna patterns in simulation environments, and to validate the analytical models proposed earlier in Chapter 5.3. Figure 4.4 in Chapter 4 shows the measurement of the realistic directional antenna patterns. For the simulation here, four directional antennas as shown in Figure 5.12 were used. Figure 5.13 shows a numerical simulation of the hub node using CST microwave studio [116] pointing N, E, S, and W.

Whilst the hub antennas may transmit simultaneously, this will only occur with very low probability. The total field produced is the sum of the individual fields, with the levels of any overlapping beam less than -10.6dB below the sector beam, in the worst case the effect of one antenna on the others beam must be less than 10.6 dB from the sector edge [18]. Since each packet will only be transmitted by one hub antenna and there is no synchronisation of transmissions, no inadvertent beamforming should occur, and it is a reasonable assumption to treat the different radiation patterns as independent from each other. Inadvertent beamforming would only be so if the transmissions were coherent and simultaneous, which may be the case if a single reference clock were used. Since any such variation is modulated by the interfering sector data, this is identified as interference not beamforming.

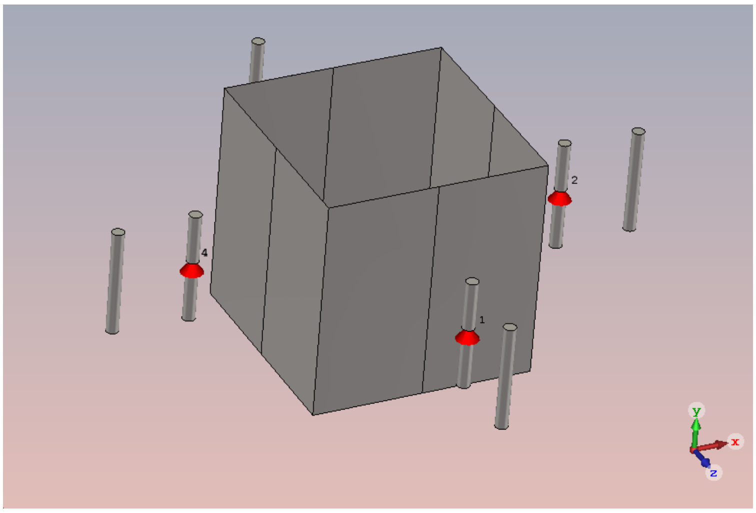

Figure 5.12: Simulation model of the quad Yagi antenna geometry showing four dipoles with reflector and director elements, with the driven element label in red.

Table 5.3. Parameters for Ant 1 (Yagi Antenna).

Antenna Parameters	Values
Dipole Length	45 mm
Director Length	43 mm
Reflector Length	90 mm
Dipole Diameter	5 mm

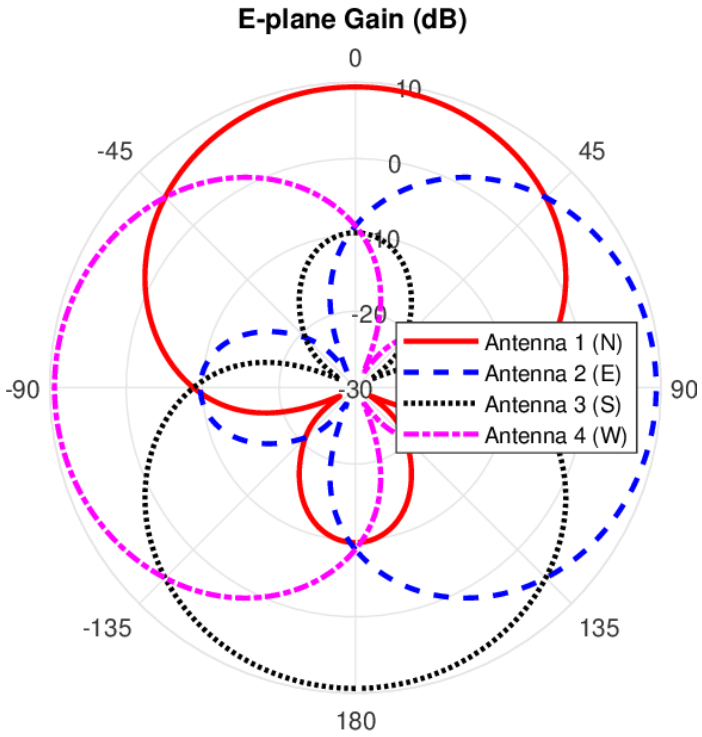

Figure 5.13: Polar plot of antenna E-plane patterns showing the extent of overlap.

From equation 5.16 and 5.17, the required SIR for Ant 1 is 10.6dB, which gives $\frac{\boldsymbol{\theta_{A0}}}{\mathbf{2}} = 70^o$, and $\frac{\boldsymbol{\theta_A}}{\mathbf{2}} = 81^o$ as shown in Figure 5.14.

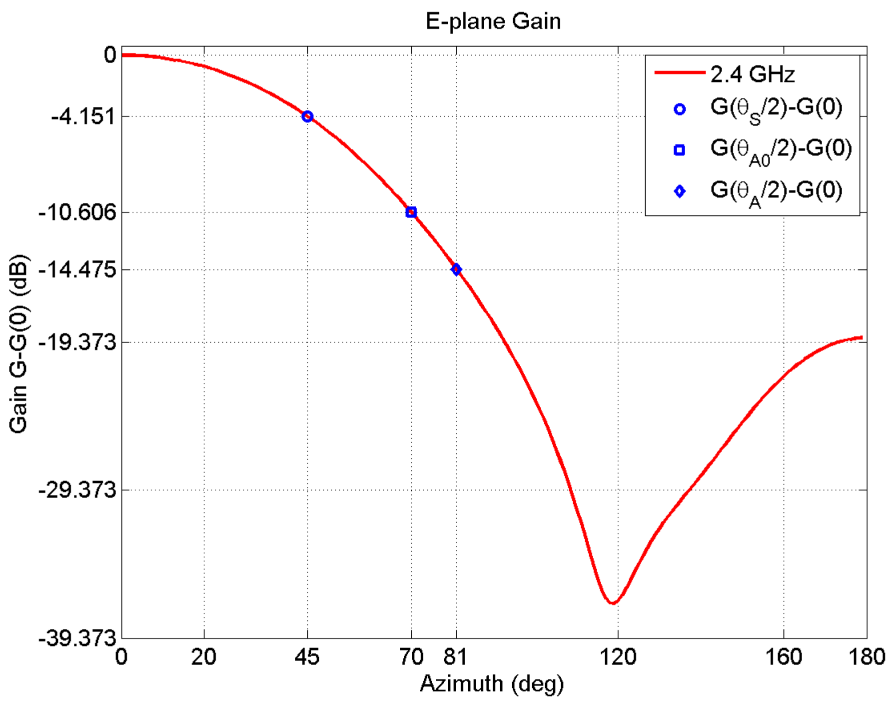

Figure 5.14: The antenna gain, relative to boresight for $M = 4$, at the sector edge ($\frac{\theta_S}{2}$), the SIR limit for boresight node ($\frac{\theta_{A0}}{2}$), and the SIR limit for node at the sector edge ($\frac{\theta_A}{2}$).

In order to evaluate the proposed DH-Aloha protocol in more realistic scenarios, the performance of the DH-Aloha protocol was simulated for 10 different randomly generated topologies. Figure 6.3 in Chapter 6 shows the throughput performance with error bars labelled, given the small deviation between the results, 10 iterations was deemed to be sufficient. The coordinates of the sensor nodes were generated using a pseudorandom generator in a 100 x 100 m^2 area and the coordinates were chosen randomly between -50 to 50. A single hub was positioned at the centre of the deployment with the coordinate of (0, 0). Different random topologies provide different performance figures due to the randomised uneven node density at each directional antenna sector. Figure 5.15 shows an example of a random topology network.

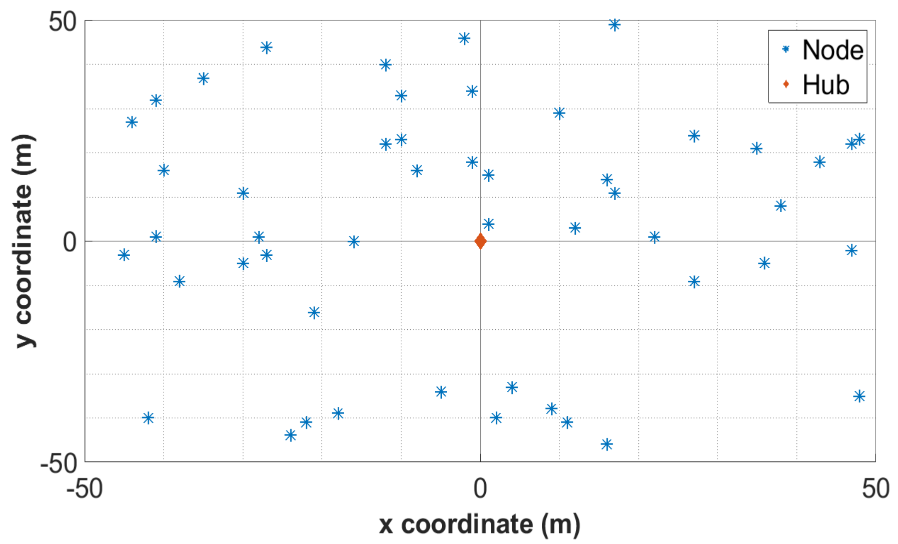

Figure 5.15: Example of random network topology with 50 sensor nodes.

Figure 5.16 compares the simulated and theoretical throughput from 10 different scenarios with four hub antennas and 50 sensor nodes. The simulated and theoretical results exhibit a very close match as shown in Figure 5.16, which confirms and verifies the analytical predictions in Section 5.3 as well as the simulation models in this section. In Figure 5.16, Ant 2 has lower throughput than Ant 1 when the offered load is larger than 0.5. It is because Ant 2 has the stronger back lobe above the SIR limits, which increases the size of overall antenna overlap region. From Equation 5.15 and Equation 5.16, the large overlap region increases θ_A and results in smaller value of r together with reduced network throughput.

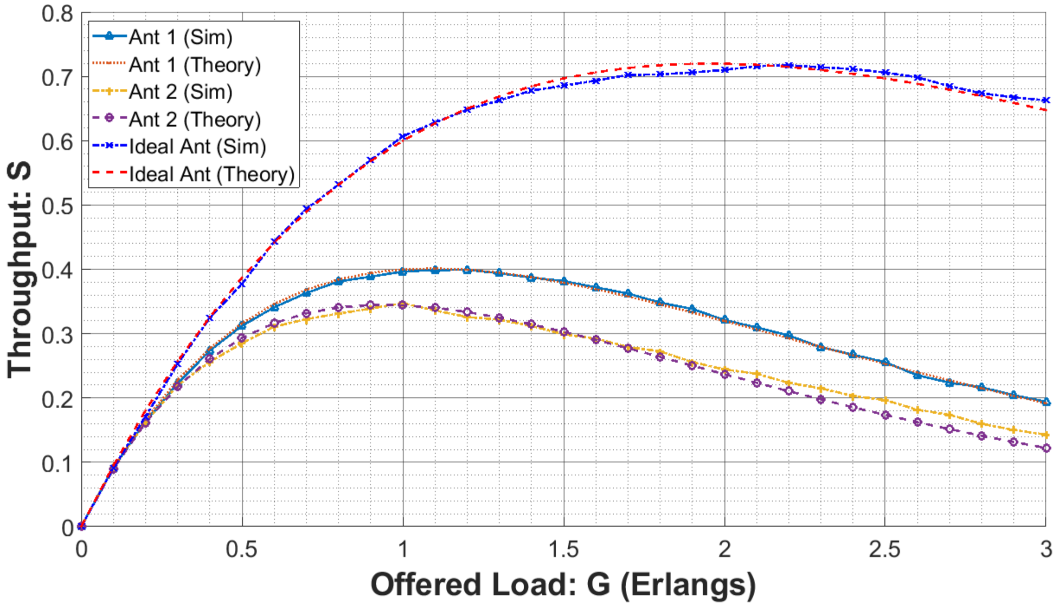

Figure 5.16: The throughput of DH-Aloha with $\boldsymbol{M} = 4$ with different directional antenna patterns, comparing theory with Riverbed Modeler simulation with 10 different random topologies.

Figure 5.17 demonstrates the change in upper bound throughput of the DH-Aloha protocol as a function of the antenna pattern overlap angle with 4 hub antennas. It shows that the overlap angle has a significant impact on the potential channel capacity. When the overlap angle is 90^o equal to θ_s in a 4 antenna hub system, the upper bound throughput is reduced by 50%. This is because the spatial reuse enhancement is effectively reduced by 50% due to the overlapping patterns.

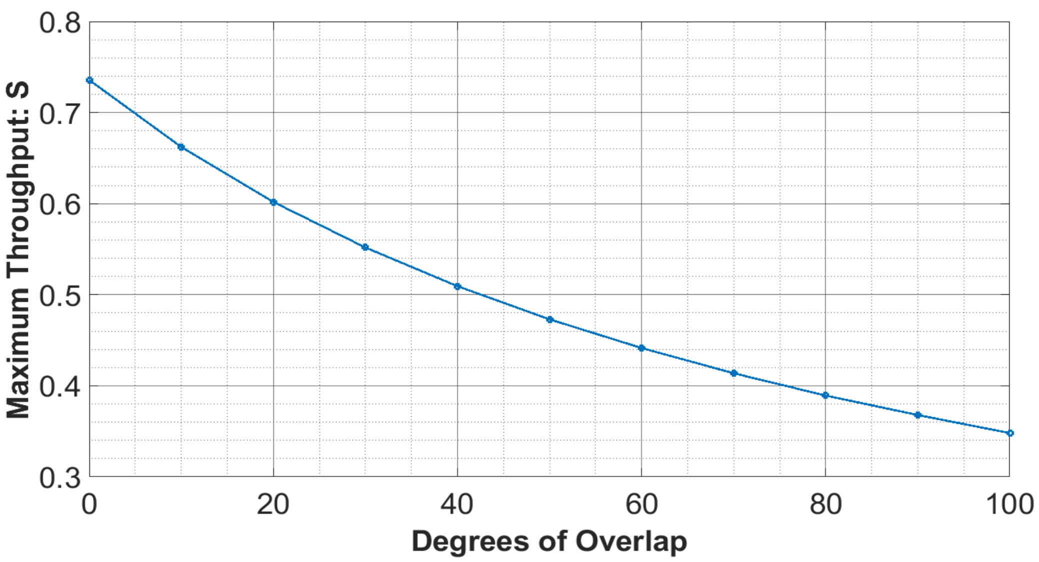

Figure 5.17: The maximum throughput achieved but the DH-Aloha protocol with different ratio of antenna pattern overlap.

5.4.3 Effect of Number of Antennas

It is demonstrated in Section 5.3 that the overall network throughput can be improved by enhancing the spatial reuse of network. Therefore, four directional antennas are introduced at the hub to cover the whole network and provide sufficient SIR for all the packets in the previous section. This section considers the effect of different number of hub antennas on the overall network throughput.

Figure 5.18 shows the maximum achievable throughput of DH-Aloha with different number of hub antennas as a function of antenna overlap factor at 50% traffic offered load. It is clear from Figure 5.18 that the maximum channel utilisation increases with the number of directional antennas at the hub. The larger number of antennas, however, are not completely related to higher channel utilisation. As it can be seen, with the same number of hub antennas, the upper bound throughput decreases as the overlap factor of the antennas increase. Although multiple directional antennas enhance spatial reuse, it might be more suitable to use less antennas for cost effectiveness in some scenarios. In the example shown, the upper bound throughput of $M = 4$ and $M = 5$ when $r = 1.49$ and $r = 1.71$ respectively, can actually be achieved with 3 hub antennas with $r = 1.2$. This is due to the fact that hub node suffers from interference caused by the antenna overlap. Therefore, the analytical model for DH-Aloha is crucial to predict its throughput performance, especially when the number of sensor nodes and hub antennas could vary.

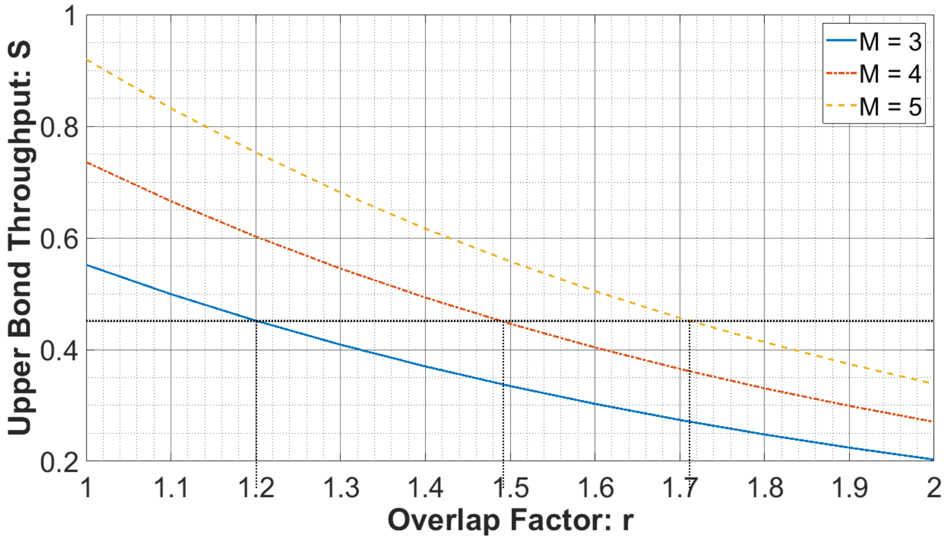

Figure 5.18: The maximum throughput comparison of different antenna number M as a function of overlap factor r with 50 sensor nodes.

The analysis in Section 5.3 considers the antenna pattern overlap effect that verifies the throughput enhancement achievable by realistic directional antennas, considering the degrees of antenna overlap. Similar analysis must be taken into consideration, as the overlap factor r is a function of the antenna effective angle θ_A, especially when deciding the number of hub antennas required for a specific WSN. Using Equation 5.13 and Equation 5.14, the achievable throughput of DH-Aloha with an antenna angle $\theta_A = 120^o$ was investigated. Figure 5.19 shows this throughput as a function of network offered load and number of hub antennas M. Table 5.4 shows the value of overlap factor r as a function of antenna angle θ_A and number of hub antenna M.

As previously stated in this chapter, overlap between antenna patterns may be required in any practical systems to ensure a full coverage of sensor nodes. When the overlap factor r is equal to 1, the directional antennas cover the WSN perfectly, with no overlap between them. This is often assumed in many studies for simplification by using idealised directional antennas. However, in practical systems, the value of r is usually between 1 and 2, meaning that the WSN is fully covered with some overlapping between antennas. When the value of r is 2 or above, it indicates the directional antennas have completely overlapped with adjacent antennas.

As seen in Figure 5.19, using the same directional antenna pattern with $\theta_A = 120^o$, the throughput performance decreases as the number of hub antennas M and the network offered load increases. The value of r for this specific antenna pattern, with $M = 2$, is 0.667 (from Table 5.4), meaning there are gaps between the hub antennas. This results in lower achievable throughput, as packets from some sensor nodes might never be received. When $M = 3$, the value of r is equal to 1. In this scenario, maximum throughput can be achieved due to the maximum enhanced spatial reuse. When the hub has 4 or 5 antennas, the overlapping antennas indicate that, although the spatial reuse enhances throughput, it is limited by the overlapping region. Although 6 or more directional antennas may provide good throughput performance under low traffic load scenarios, the performance decreases significantly as the traffic increases. This is caused by the completely overlapping antenna patterns.

Therefore, previous analysis and the results presented in Table 5.4 are crucial in deciding the correct number of hub antennas when applying the DH-Aloha protocol to WSNs, as this allows the maximum throughput with the minimal amount of hub antennas, based on the specific antenna pattern.

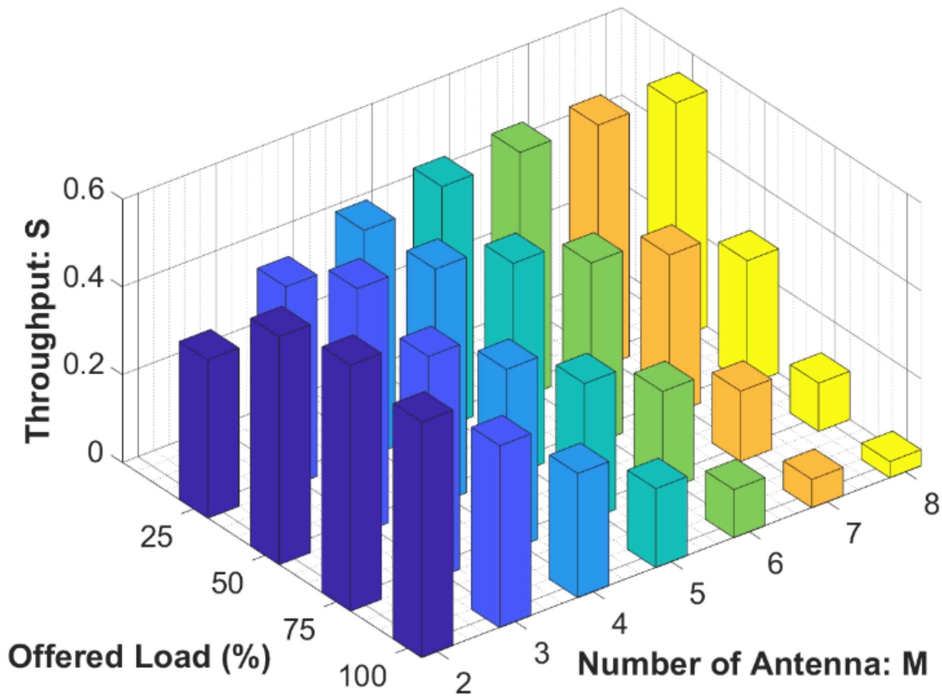

Figure 5.19: The maximum achievable throughput comparison of different antenna number M as a function of network offered load with 50 sensor nodes and $\theta_A = 120^o$ using Equation 5.17.

Table 5.4. Values of overlap factor r as a function of antenna angle θ_A and number of hub antenna M.

Directional Antenna Angle θ_A

Number of Antenna M	90	100	110	120	130	140	150	160	170	180
2	0.500	0.556	0.611	0.667	0.722	0.778	0.833	0.889	0.944	1.000
3	0.750	0.833	0.917	1.000	1.083	1.167	1.250	1.333	1.417	1.500
4	1.000	1.111	1.222	1.333	1.444	1.556	1.667	1.778	1.889	2.000
5	1.250	1.389	1.528	1.667	1.806	1.944	2.083	2.222	2.361	2.500
6	1.500	1.667	1.833	2.000	2.167	2.333	2.500	2.667	2.833	3.000
7	1.750	1.944	2.139	2.333	2.528	2.722	2.917	3.111	3.306	3.500
8	2.000	2.222	2.444	2.667	2.889	3.111	3.333	3.556	3.778	4.000

5.5 Summary and Conclusion

This chapter investigates the fundamental behaviour and performance of the combination between contention-based MAC protocol and directional antennas. Starting with the traditional Pure Aloha protocol, a number of procedures are discussed and evaluated to enhance its performance.

The Pure Aloha protocol provides a key advantage of simplicity, low end-to-end delay, and low energy consumption. However, it has the drawback of low channel capacity due to a blind transmission strategy, especially under a high traffic load. Previous work has concentrated on the performance of DMAC protocols with a number of simplifying assumptions. The work presented in this chapter focus on the limitations and constraints of directional antennas to further improve the fundamental performance of the protocol.

In the DH-Aloha protocol, the hub is equipped with directional antennas. A fundamental feature of this approach is that sensor nodes are allowed to access any of the directional antennas of the hub, which enhances the spatial reuse. DH-Aloha only requires additional hardware at the hub station, which retains the simplicity and low energy consumption of the sensor nodes. Simulation models presented in this chapter have been implemented using Riverbed Modeler. It has been shown that the scheme can provide good overall network throughput compared to the traditional Pure Aloha. However, the performance of the protocol degrades due to the effects of antenna pattern overlap. An analytical model has been proposed to estimate the actual throughput improvement based on the number of directional antennas at the hub, the ratio of antenna pattern overlap and the number of nodes within the network. Another interesting finding is that by reducing the ratio of antenna pattern overlap even further, the maximum throughput of the WSN can increase towards M times that of a single antenna Pure Aloha network.

A novel analytical technique is developed to evaluate the performance of the DH-Aloha scheme. This technique is based on the combination of graphical and mathematical analysis and can be used to predict the throughput performance of the DH-Aloha scheme prior to the implementation, which potentially saves significant development time and cost. The performance of these schemes are evaluated using a common set of simulation models and the results match well with the theoretical analysis as the validation.

Significant contributions and advances have been made to further improve the effectiveness of a contention-based power control MAC protocol with directional antennas. It is clear that such a scheme can provide better throughput performance. However, the benefits of spatial reuse highly depend on the directional antenna pattern. Specifically, the performance of this protocol is constrained by the overlap ratio of the antenna patterns. Hence the proposed analytical model for throughput is essential to predict the performance of a realistic WSN scenario. A novel approach to improve performance metrics such as fairness and energy efficiency of the DH-Aloha scheme will be presented in Chapter 6.

Chapter 6 DH-Aloha with Power Control

Contents

6.1 Introduction

Although directional MAC protocols such as those reviewed in Chapter 3 and the Directional Hub Aloha (DH-Aloha) protocol investigated in Chapter 5 have shown to be a powerful approach to throughput performance enhancement, their common disadvantage is the lack of consideration of power consumption, which significantly limits their adaptability and lifetime in challenging and potentially dynamic traffic environments, for example when nodes are mobile. In previous work on a directional contention-based MAC protocol [15], researchers have only considered applying directional antennas to enhance throughput performance with no regard for, or consideration of other metrics such as energy efficiency and fairness. One of the promising solutions to this issue, is to apply a power control strategy at the sensor node. Its goal is to reduce the sensor node energy consumption by dynamically adjusting the transmission power. For example, Le *et al* [117] proposed an energy effective MAC protocol for a mobile WSN with reconfigurable directional antennas to provide both throughput and energy efficiency improvements.

The purpose of this chapter is to alleviate the problem of poor energy efficiency and lifetime performance of directional MAC protocols and, thus, to improve their adaptability, lifetime, and fairness, by proposing a power control strategy which combines dynamic transmission power control and the contention-based random access technique.

In the previous chapter, it is shown that the use of directional antennas has a significant effect on network throughput drawing on the advantage of spatial reuse. In this Chapter, the primary objective is to look at the potential benefits of combining the use of directional antennas at the hub with a power control strategy at the sensor nodes. This power control strategy incorporates transmit power adjustment at the start of each data packet transmission, in contrast to the traditional protocols where nodes transmit with maximum transmit power. As a result of the use of the power control strategy, the sensor node energy efficiency and the overall network fairness can be significantly improved. The concepts and contributions introduced in this chapter have resulted in the following publication [118].

The Directional Hub Aloha protocol with Power Control (DH-Aloha-PC) is introduced in Section 6.2. A detailed description of the functionality and operation of the protocol is given, followed by the simulation setup in Section 6.3. The performance evaluation and analysis are presented in Section 6.4, based on a combination of graphical and mathematical analysis. This chapter ends with a summary in Section 6.5.

6.2 Directional Hub Aloha with Power Control

The simplest possible implementation of the power control strategy is to allow sensor nodes to transmit with different transmit power levels which are dynamically adjusted according to their needs without any additional complexity at the sensor nodes. The required transmit power is calculated at each individual sensor node using the received packets from the hub node. The required transmit power is an estimation of what is required to achieve successful reception at the hub whilst avoiding excess energy usage at the sensor node. All sensor nodes transmit data packets on a best effort basis. The DH-Aloha protocol with power control (DH-Aloha-PC) represents a modified implementation of the DH-Aloha protocol from Chapter 5. Similar to the traditional Aloha protocol, the inter-arrival time for the data packet generation is exponentially distributed. In order to retain low end-to-end delay whilst performing power management, additional acknowledgement (ACK) packets following each successful data transmission have been implemented instead of overhead control packets prior to data transmission. Algorithm 1 summarises the steps of the proposed power control DH-Aloha protocol for WSNs.

Algorithm 1 DH-Aloha-PC MAC protocol algorithm. N_retry is the number of retries for the current data packet, P_tx is the packet transmit power, cd_DATA is the counter for sensor nodes after transmitting DATA packets, and R_max is the maximum value for retries.

```
for each packet arriving queue do
  if ongoing transmission = 0 then
    reset N_retry = 0
    Send DATA to receiver with P_tx
    Start countdown timer (cd_DATA)
      if ACK received && cd_ DATA > 0 then
            Packet transmission successful
            Update P_tx based on the ACK received power
      else
            Update P_tx to maximum
            if retransmission = 1 && N_retry < R_max then
              Send DATA to receiver with P_tx
              N_retry = N_retry + 1
```

At any instant in time each sensor node exists in one of three possible states: TX if there is a requirement for data packet transmission, RX if waiting for an ACK packet, and SLEEP if there is no requirement for capacity. Sensor nodes toggle between the three states as required, but a sensor node cannot be in more than one state at the same time. Each sensor node keeps a value of preferred transmit power (P_p) and uses it for subsequent transmissions. A sensor node will transmit a data packet as soon as it arrives in the queue, providing it does not have any on-going transmissions. If this is the first packet the sensor node has to transmit, where there has not been a previous ACK reception, the preferred transmit power value (P_p) will be set to the maximum P_{t_max}. The sensor node will enter the RX state and wait for an ACK packet from the hub indicating a successful reception. The sensor node will record the received power of the ACK packet for the purpose of power management. The sensor node calculates the minimum required transmit power for a successful reception using the received power of the ACK by assuming a reciprocal propagation path. Here it is assumed that the hub has a constant transmit power. The minimum transmit power can be updated from Equation (6.1). The preferred transmit power value (P_p) is then updated by the new minimum transmit power. If P_p is less than the minimal achievable transmit power of the sensor node, then P_p will be updated with the minimum transmit power allowed by the sensor node.

$$P_{T,node} = \frac{P_{T,hub}}{P_{R,node}} \ P_{R,hub} \tag{6.1}$$

where $P_{T,node}$ is the required node transmit power to achieve the required hub receive signal power $P_{R,hub}$, if the measured node received power is $P_{R,node}$ and the hub transmit power is $P_{T,hub}$.

If an ACK packet is not received after the expected timeframe, typically just longer than the round trip time of the packet (RTT), the sensor node will reset P_p to the maximum value for the next packet transmission, or subsequent retransmission if enabled. The sensor node will re-transmit the data packet until an ACK is received, or it reaches its retry limit. By doing so, this strategy avoids the need for the sensor node to continuously monitor the channel to observe the hub signal strength, thus saving energy. If a data packet arrives at the queue during an on-going transmission, then the data packet will be added to the back of the queue. Upon receiving an ACK or the retry limit being reached, the sensor node's queue is checked for further packets, and the queued data packets will be dealt with immediately one after the other until the queue is empty on the basis of a First-In-First-Out (FIFO) discipline. The most obvious strategy for a sensor node to enter a SLEEP state is when the last packet in the queue has been acknowledged, leaving an empty queue.

When the hub antenna has the highest gain (i.e. when sensor node is at the centre of the main lobe), the sensor node requires the lowest transmit power; hence the minimum limit for node transmit power. However, in a mobile network under low traffic load, the time difference between the sensor node receiving the ACK and transmitting the next packet might indicate that the transmit power is no longer sufficient. This is because the gain of the receiver is no longer the same as when the ACK is transmitted due to the mobility of the sensor node, and a higher transmit power is required to maintain the required hub receive signal power. On the other hand, when the sensor node speed is high, the sensor node transmit power also might not be sufficient. This is because the distance travelled by the sensor node between receiving the ACK and transmitting the next packet might result in a longer propagation distance or a lower receiver antenna gain. Although this power control scheme can improve the energy efficiency for static WSNs while trying to maintain the same level of throughput performance; the throughput discrepancy of applying this power control scheme in mobile scenarios will be discussed later in this chapter.

On the other hand, the hub protocol is a little more complex, as any packet from a node may be received by more than one hub antenna. The MAC protocol must deal with duplicate packets at the hub and decide on the optimum antenna with which to communicate with any node and which of the duplicated packets to discard. From the point of the hub node, the protocol corresponds to the traditional Aloha protocol with the addition of the ACK packet used for power control and the need to track which antenna received the best packet from a node in terms of signal-to-interference-plus-noise ratio (SINR). Retransmission can also be enabled depending on the WSN application requirement. It is assumed that the sensor nodes may move, as well as obstacles and other sources of interference, so the optimal directional antenna and the node transmit power must be allocated dynamically. A disadvantage of this technique is that the P_p of each sensor node might be inaccurate if an obstacle or interferer moves into the reciprocal path between the instants when the ACK is received and the next data packet is ready to transmit.

6.3 Simulation Model and Implementation Details

A single set of Riverbed Modeler simulation models have been developed which provide a platform for implementing any of the DH-Aloha variants. The randomly generated topology scenarios in Chapter 5 have been chosen for the simulations to provide an overview of the network performance. The reasons for this approach are that the two MAC protocols have significant commonality in their functionality. It is more effective to develop a single set of simulation models that provides the core functionality and operate with the alternative transmission power strategies. Furthermore, it enables a more effective performance comparison of the different schemes. The simulation parameters and network pipeline stages have been modified with the simulation parameters presented in Table 6.1. Since different WSN applications might require different mobility as stated in Chapter 2, different sensor node speeds are considered for performance evaluation.

Free space propagation is considered for all communication and the sensor nodes are not allowed to start a new transmission if they are currently receiving, since the hardware would prevent it. Since there is no synchronisation between sensor nodes in contention-based protocols, packet reception is governed by the received SINR, assuming uncoded binary phase shift keying (BPSK) modulation as an illustrative example. A look up table is used to acquire the bit error rate (BER) corresponding with the received SINR level for each bit. This BER value is used to determine whether each individual bit is received in error, based on the generation of a uniformly distributed random number between zero and one. This BER value is then compared with the BER threshold, and one or more bit errors would result in a discarded packet. The power control strategy is evaluated with the directional antennas previously mentioned in Chapter 4 presented in Figure 4.4 and Figure 4.5.

Table 6.1: Simulation Parameters for DH-Aloha-PC

Parameters	Values
Frequency Band	2.4 GHz
Number of nodes	50
Channel Data Rate	250 kbps
Data Packet Length	1024 bits
Acknowledgement Packet Length	8 bits
Maximum Transmit Power	0.01 W
Network Grid Size	100 x 100 m
Sensor Node Speed	0, 2, 5, 10, 20, 40 mile/hour

6.4 Performance Evaluation of DH-Aloha with Power Control

The purpose of this set of results is to present the performance of the DH-Aloha protocol with the power control strategy, show how different features of a WSN can benefit from the applied power control scheme, and investigate the performance improvements that can be achieved using it in terms of the QoS provided to the sensor nodes.

Figure 6.1 illustrates the average transmission energy per bit required for successful transmission. This is calculated by dividing the product of the transmission time and transmission power level by the number of successfully received bits. The required energy per bit relates to the proportion of data bits that are successfully received without collision, in which the density of the network traffic load is the major factor in a contention-based protocol.

At high traffic loads, since the number of sensor nodes contending for the channel in a given interval increases, the energy required per bit would also increase due to the higher probability of collision. Therefore, as the number of attempts for a successful transmission becomes higher compared to lower traffic loads, we see a higher energy requirement per successful packet delivery. Compared to the DH-Aloha protocol, the transmission power of the sensor nodes can be reduced by a factor of two on average by employing the new strategy. One of the goals of this power control strategy is to prolong the lifetime of the sensor nodes and thereby the network lifetime. The lifetime estimation (T_{life}) of a sensor node can be expressed as [119]:

$$T_{life} = \frac{C_b}{{I_s}^k} \tag{6.2}$$

where C_b is the capacity of the battery in Ah, I_s is the sum of the current consumption needed for the sensor node, and k is the Peukert constant, which depends on the battery type.

To estimate the sensor node energy consumption, E, the energy consumption can be expressed as:

$$E = \left(I_{tx}\, T_{Tx} + I_{rx}\, T_{rx} + I_{sleep}\, T_{sleep}\right) * V \tag{6.3}$$

where V is the supply voltage, T_{Tx}, T_{rx} and T_{sleep} denotes the time of which the sensor node stays in TX, RX and SLEEP states respectively. I_{tx}, I_{rx}, and I_{sleep} represent the current draw when the sensor node is in TX, RX and SLEEP state respectively, in which I_{tx} depends on the power control strategy.

In this estimation, the current draw of the microprocessor control unit (MCU) is not considered as we are focusing on the energy consumed during communication. The current consumption I_s can be expressed as:

$$I_s = \frac{E}{t} \tag{6.4}$$

where t is the overall time period.

In order to estimate the lifetime of the sensor nodes, the quoted values of current consumption values from MICAz mote [22] are adopted. Two 1.5V batteries rated at 2000 mAh each are assumed for each sensor node, in which the current draw is assumed to be fixed. Figure 6.2 shows the numerical comparison of the expected lifetime obtained from the DH-Aloha MAC protocol variants. This is calculated by dividing the product of the total number of bits transmitted (N_b) and the transmission power level (P_{tx}) by the number of successfully received bits (N_s). The energy per successful bit ($EpSb$) can be defined as:

$$EpSb = \frac{N_b \, . P_{tx}}{N_s} \tag{6.5}$$

It can be observed that the energy required per bit increases as the traffic offered load increases. Since the increased probability of collision causes a greater number of lost packets, the number of attempts for a successful transmission becomes higher. Therefore, the energy required per successful transmission increases.

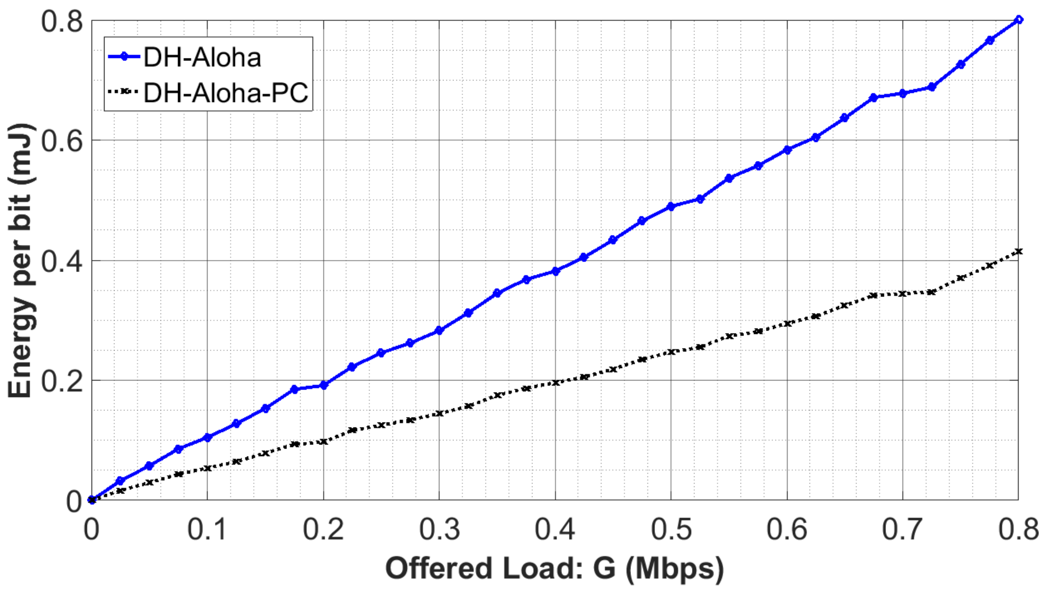

Figure 6.1: Node transmission power management.

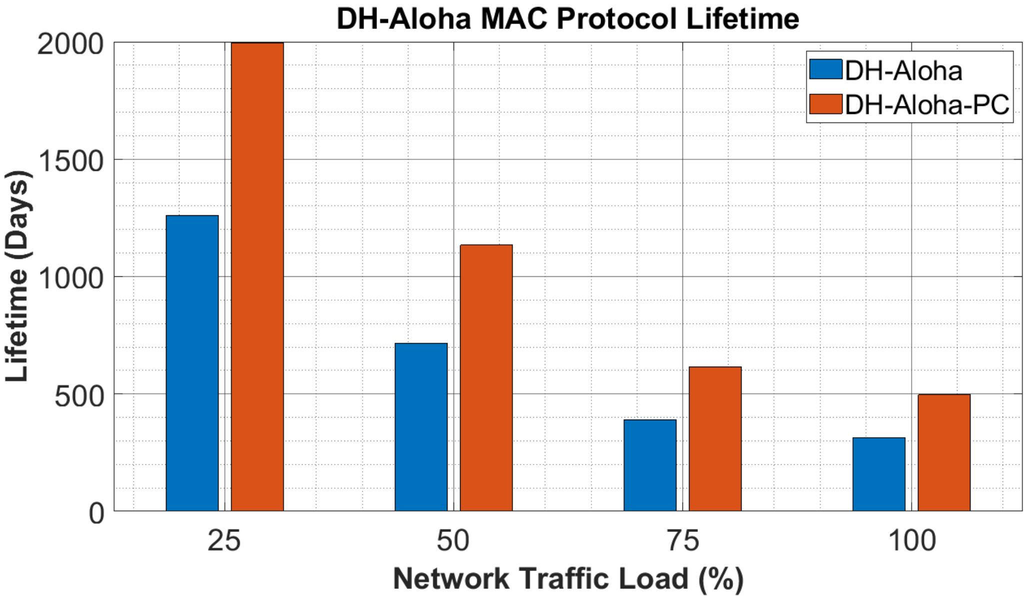

Figure 6.2: Comparison of expected sensor node lifetime with DH-Aloha MAC protocol variants.

Figure 6.3 presents the average throughput of the DH-Aloha-PC protocol, comparing it with the traditional Pure Aloha protocol and the DH-Aloha protocol. It can be seen that the throughput of DH-Aloha-PC is better with respect to the DH-Aloha protocol. This is due to the power control strategy which serves to reduce the antenna pattern overlap, resulting in a reduction in packet collisions. Deducing from Equation 5.13 and Equation 5.14 in Chapter 5.4, the power control strategy reduces the data packets received power at the hub outside $\boldsymbol{\theta_s}$. This results in the increased SIR value from Equation 5.13 and Equation 5.14 in Section 5.4, and a reduction of $\boldsymbol{G}\ (\frac{\boldsymbol{\theta_{A0}}}{\boldsymbol{2}})$ and $\boldsymbol{G}\ (\frac{\boldsymbol{\theta_{A}}}{\boldsymbol{2}})$. Hence, reducing the value of $\boldsymbol{\theta_{A0}}$ and $\boldsymbol{\theta_{A}}$. The results show that the throughput performance can be significantly improved by using multiple directional antennas at the hub, where good throughput performance can be guaranteed beyond the practical limits of the traditional Aloha protocol when it becomes unstable (at an offered load of over 1 Erlang). In a practical one antenna system, 1 Erlang is the practical limit of the throughput performance assuming no overheads. Ideally, when all directional antennas share the network equitably in a M antenna system, M Erlangs can be achieved assuming no overheads. A marginal improvement in throughput can also be provided by the additional power control strategy.

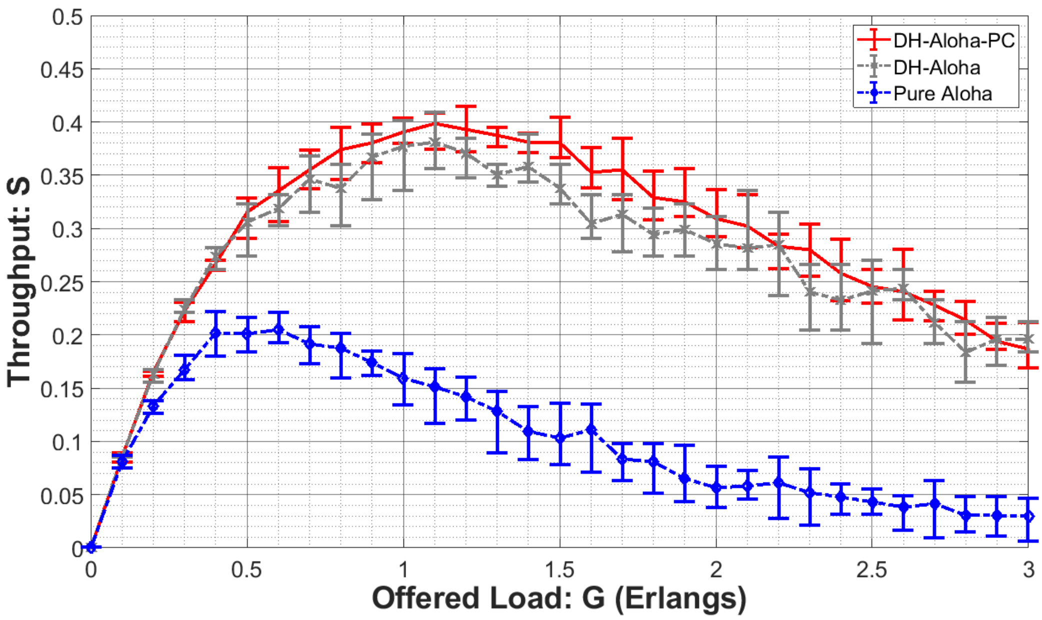

Figure 6.3: The throughput of DH-Aloha-PC illustrating the improvement in throughput offered by the use of directional antennas and power control strategy.

As SINR is a function of path loss, which takes into account the antenna gains and the propagation distance, packets propagating over a short distance will have a higher SINR than packets propagating over a long distance. As a result, short distance packets will have a higher successful reception rate in a system without any power control mechanism. Hence, a high overall network throughput does not necessarily mean a fair network. The individual throughput of each sensor node must be considered in order to design a MAC protocol for fair access across a WSN. Only if the overall throughput is equally contributed from all the sensor nodes, can the network be assumed to be fair. In MAC protocols where transmission power control does not exist, sensor nodes closer to the hub will likely dominate the channel due to the shorter propagation distance and the higher receiver antenna gain. An unfair network does not affect the overall network throughput as the total number of data packets received successfully at the hub will be the same.

Figure 6.4 to Figure 6.6 demonstrate that the DH-Aloha-PC improves the fairness of the network. Figure 6.4 (a) shows the successful packet reception rate with respect to the DH-Aloha-PC protocol as a function of propagation distance, and the successful packet reception rate for DH-Aloha is shown in Figure 6.4 (b). Jain's fairness index is a fairness performance metric used in communication systems, it is defined by R. Jain [109] as stated in Chapter 4 Equation 4.8. The fairness index ranges from $\frac{1}{n}$ to 1, where n is the number of nodes in the network. Ideally, when all sensor nodes share the channel equally, the fairness index will be equal to 1.

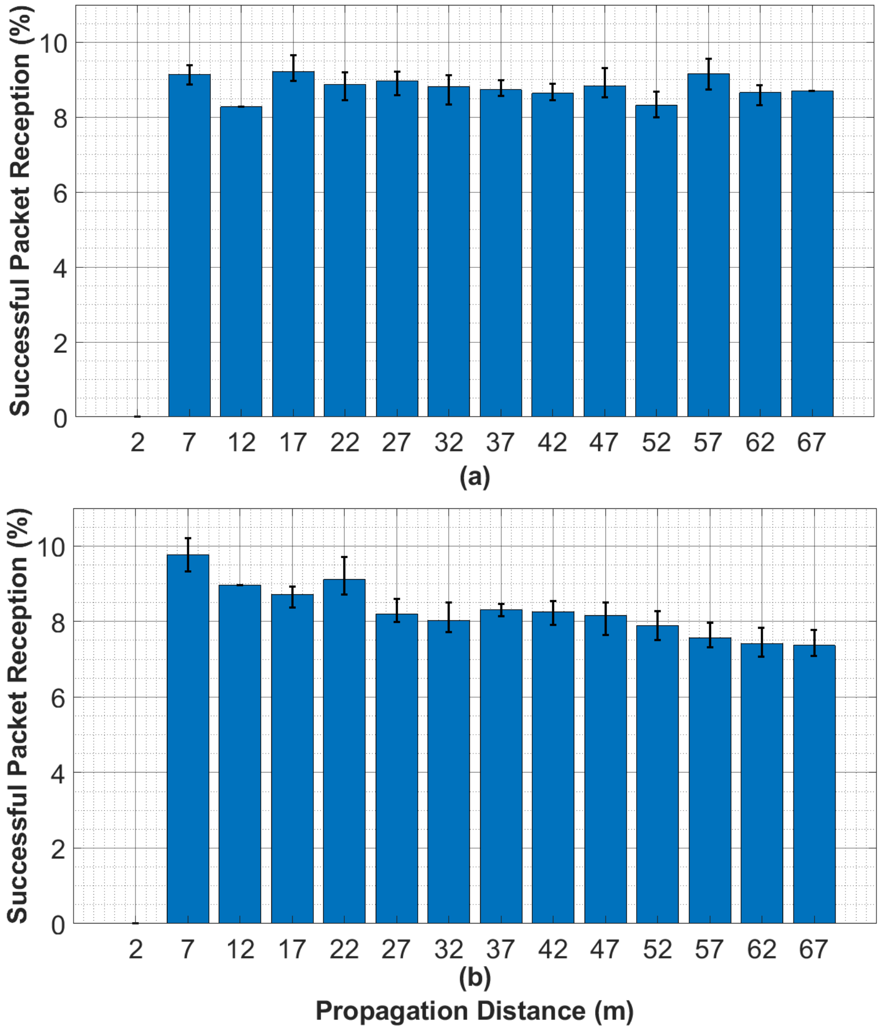

Figure 6.4: Successful transmission as a function of distance from the hub with (a) and without power control (b).

Figure 6.5 presents the fairness performance of the DH-Aloha protocol variants as a function of offered load. It can be seen that the power control scheme provides a significant improvement in the fairness index, especially at medium to high offered loads. Since the DH-Aloha protocol is a random access scheme, fewer sensor nodes are transmitting at low offered load allowing packets from nodes further away from the hub or with lower received antenna gain to be received successfully without interference. However, in heavy load scenarios, more nodes are transmitting in a given interval, packets with longer propagation distance or lower receiver antenna gain suffers from interference. This causes an uneven SINR from different sensor nodes, which worsens fairness performance.

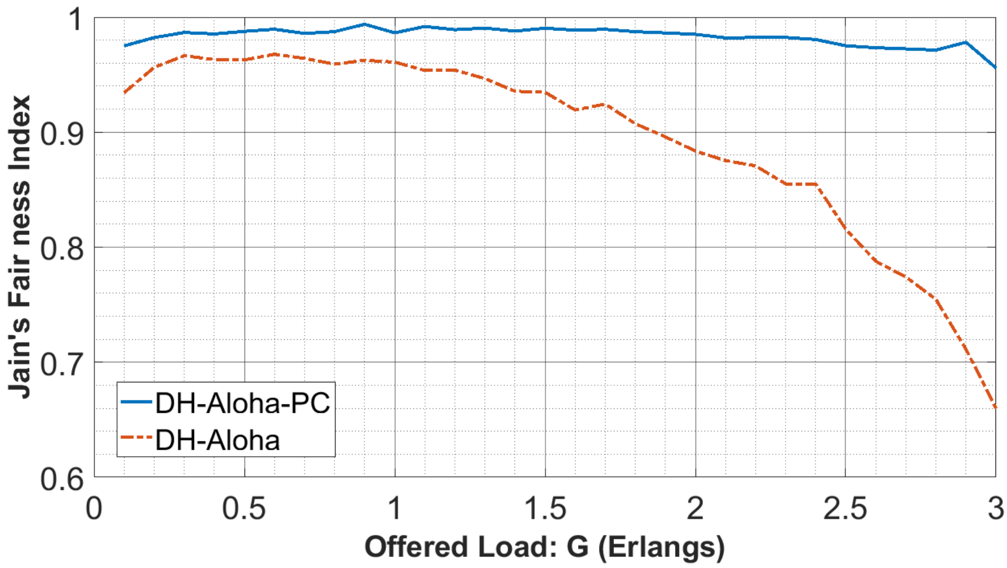

Figure 6.5: Jain's fairness index with the power control strategy applied in a WSN with 50 nodes.

Figure 6.6 shows the number of nodes that achieve a given level of packet reception success, in the form of a bar chart and based on the percentage of packets that are successfully received. As shown in the figure, the results show a Gaussian shape distribution. Comparing the successful packet reception of the two schemes with 50 sensor nodes, it can be seen that DH-Aloha-PC provides a low variation in the number of nodes experiencing different levels of packet reception success. The majority of the sensor nodes achieve similar success packet reception values, and the results highlight the improvement it provides for the per-sensor node throughput and fairness.

It can be observed from these plots that a suitable power control strategy is required to maintain reasonable throughput and provide adequate fairness performance. Sensor nodes located far away from the hub may suffer from low individual throughput, especially in high traffic offered load scenarios.

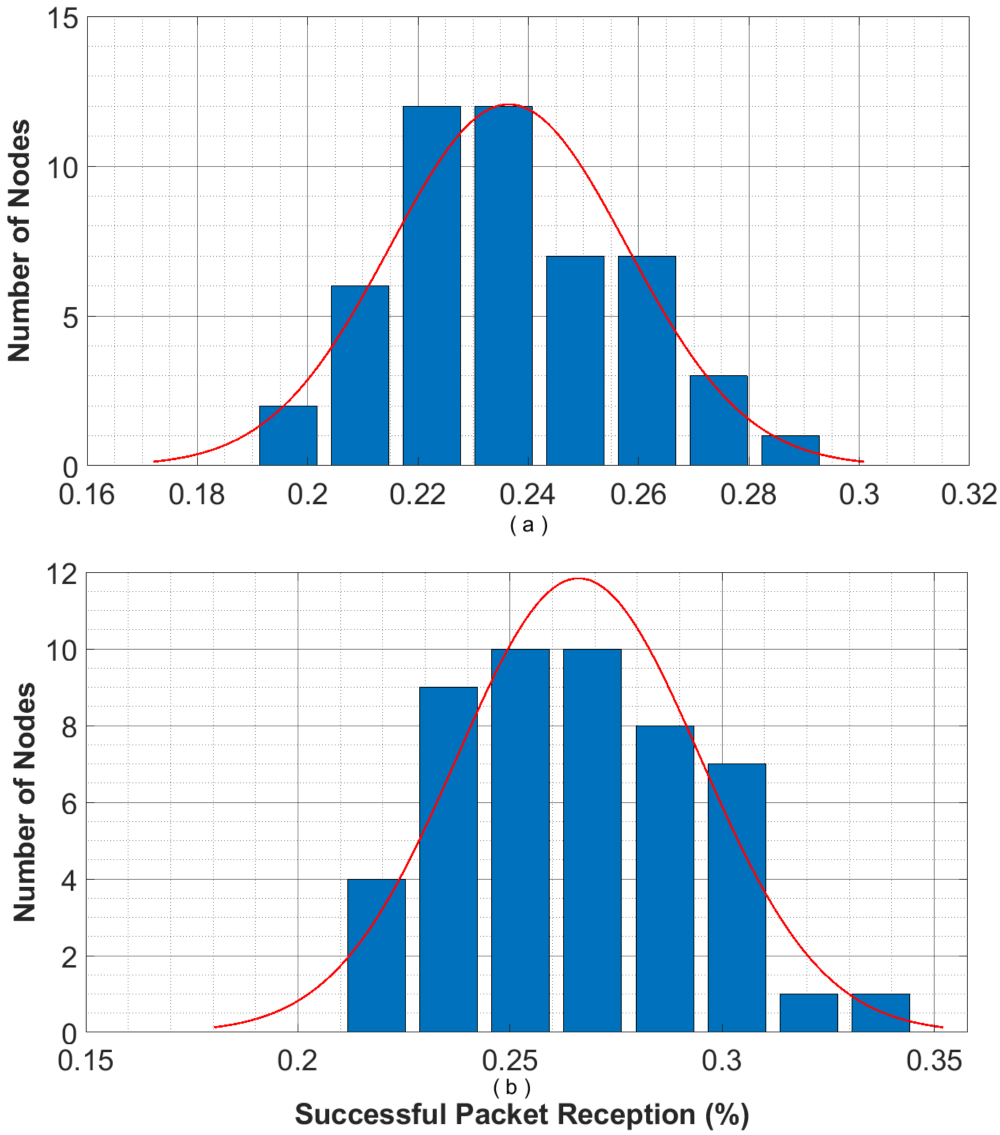

Figure 6.6: The proportion of success packet reception rate for DH-Aloha-PC with 50 sensor nodes and the channel traffic offered load of 50% (a) and 100% (b).

Figure 6.7 shows the throughput of the DH-Aloha-PC protocol averaged over the 10 topology scenarios for three directional antenna types, Ant 1, Ant 2 and the ideal sector antenna. As the idealised sector antenna pattern has no overlap between sectors, a substantially larger throughput can be achieved with the real antennas with patterns that have some overlap. It can be observed from Figure 6.7 that the power control strategy can be applied to WSNs with any directional antenna pattern, providing the same level of network throughput performance.

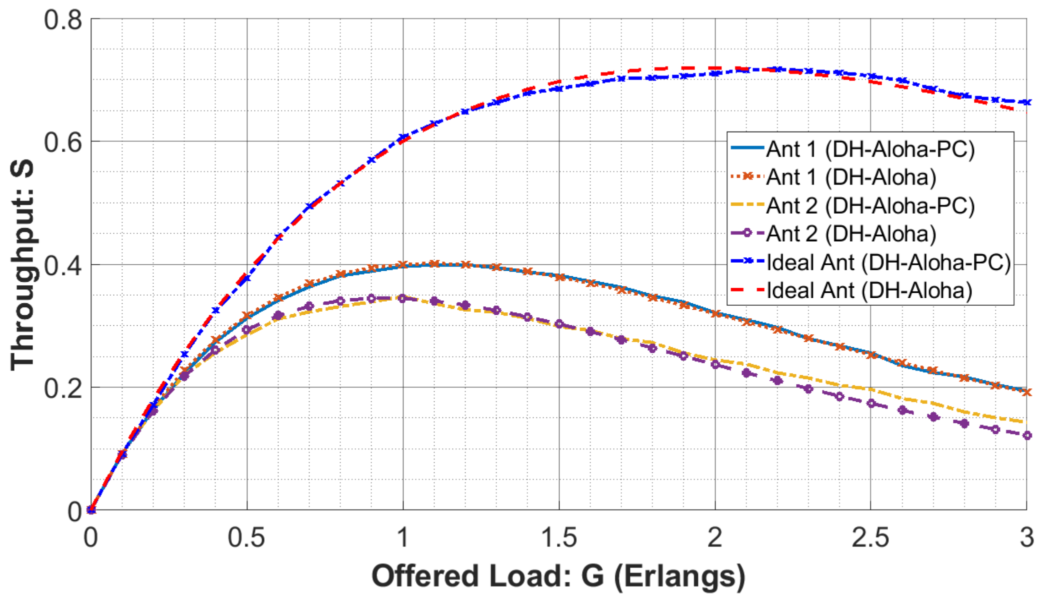

Figure 6.7: Throughput comparison of different directional antenna patterns with the DH-Aloha-PC protocol.

The feasibility of the DH-Aloha-PC can be evaluated from the cost effectiveness of the protocol. The cost effectiveness of DH-Aloha-PC is achieved from two aspects. The cost of the sensor nodes will not be affected despite the enhanced performance, as only the hub will be equipped with the additional hardware. The increased gain of the directional antennas at the hub can also reduce the transmission power required at the sensor nodes, therefore resulting in a longer lifetime of the nodes and the network. In order to allow the topology to be as flexible and compatible as possible, nodes are not required to be synchronised. This can allow any sensor nodes to be added or removed from the network at any time without disrupting the network operation.

With consideration of the mobility of the WSN, the hub and the sensor nodes are not reliant on the knowledge of their own location, nor the position of the destination. By dynamically adjusting their transmission power by collecting and analysing the information from the hub packets, the efficiency and performance can be maximised. To consider the link performance of applications with mobile WSNs, simulation models have been implemented with the DH-Aloha protocol. A set of coordinates are randomly generated for each sensor node at the beginning of the simulation locally, in which the hub node will have no knowledge of the coordinates. The sensor nodes will move from one coordinate to the other at a predetermined constant speed. All sensor nodes move independently of one another. Figure 6.8 depicted the average throughput discrepancy for the mobile scenarios as opposed to the stationary scenarios. As seen in Figure 6.8, the throughput discrepancy increases as the sensor node speed increases. Since the sensor node uses the ACK packet from the previous communication to adjust the transmit power of the next data packet. The high speed might significantly affect the SINR of the data packet. Therefore, exposing the data packet to a higher probability of packet collision. However, the results in Figure 6.8 emphatically show that it is possible for the DH-Aloha-PC protocol to be deployed on a mobile WSN scenario that is capable of providing reasonable service in a challenging dynamic environment, but with no need for additional hardware and complexity, and with no significant degradation in the primary quality of service (QoS).

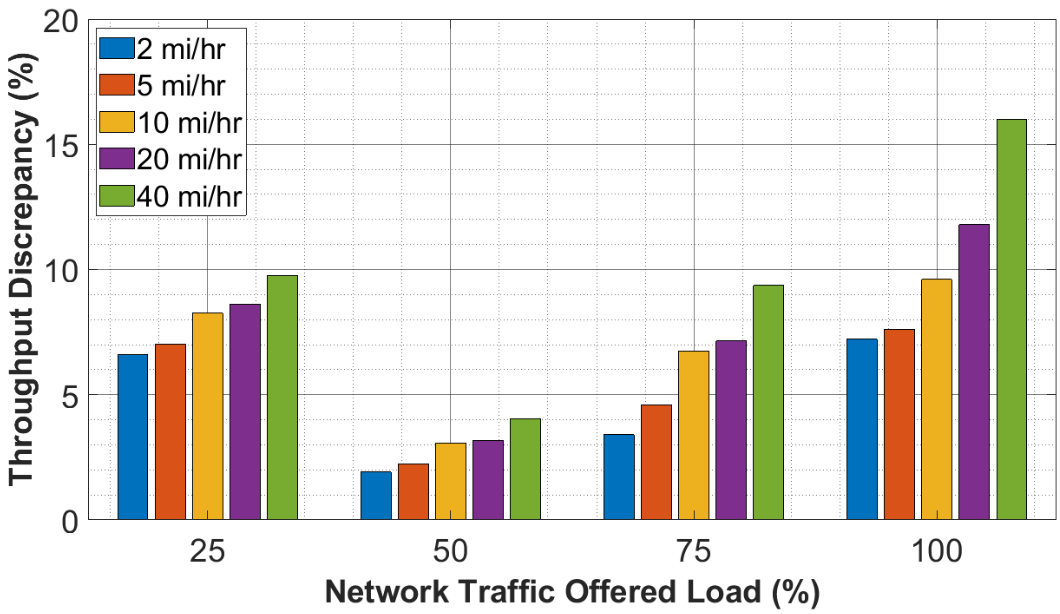

Figure 6.8: The mean throughput error of DH-Aloha-PC MAC in mobile scenario as a function of channel traffic offered load over static scenario.

6.5 Conclusion

This chapter has looked at the fundamental behaviour and performance of a directional MAC protocol combining a contention-based random access technique and a dynamic power control strategy. Starting from the work presented in Chapter 5, a variant of the DH-Aloha MAC protocol has been introduced which differs in its provision for assigning transmission power for data packets in a single hub centralised network. This scheme has addressed the issue of energy efficiency, fairness and network lifetime, by adjusting the node transmission power. The performance of DH-Aloha-PC has been evaluated through a common set of simulation models with DH-Aloha, and the results obtained have been compared with those presented in Chapter 5. Previous work in Chapter 5 has concentrated on the influence of the directional antenna patterns on the network throughput performance. The work presented in this chapter has focused on the potential of transmission power control, with a view to improving the fundamental performance in terms of energy efficiency, network lifetime and fairness of the protocol for a wider range of topology scenarios.

In the DH-Aloha-PC scheme, each data packet transmission attempt is dynamically controlled. A fundamental feature of this approach is the potential for using ACK packets from the hub to determine the required SINR for a successful reception under a dynamically challenging radio environment. It has been shown that the scheme can provide the same level of network throughput performance as the DH-Aloha protocol, and that it does not suffer from fairness problems or high energy demand under reasonable traffic loads. The performance of the scheme does degrade a little when operating in a mobile scenario. However, the degradation is only minor with considerable improvement in other metrics.

Significant contributions and advances have been made to the effectiveness of a combined multi-directional antenna contention-based MAC protocol and transmission power control strategy and it is clear that such scheme is able to provide better channel utilisation and energy performance compared with those incorporating a single antenna protocol. However, the throughput performance is limited by the directional antenna patterns and the random channel access behaviour. The only way to provide any further improvements in the throughput performance whilst retaining other benefits is to find an alternative means of contention-based channel access, considerably different from the other techniques. A novel approach incorporating the contention-based approach and the power control strategy has been invented and the advances are presented in Chapter 7.

Chapter 7 Virtual Sensing Directional Hub Aloha Protocol

Contents

7.1 Introduction

Due to the unpredictability and statistical uncertainty of interference and data traffic, current Medium Access Control (MAC) protocols employ directional antennas to achieve a high useful channel capacity. The performance of this technique is constrained by the antenna pattern and the number of directional antennas as stated in the previous chapters. Directional MAC (DMAC) protocols are often designed based on a number of simplifying assumptions, but as shown in the material presented in Chapter 5, these protocols are only effective in an ideal scenario. The limitation on the DMAC protocols results in the need to design novel yet realistic MAC protocols to account for these realistic phenomena.

This chapter introduces a new DMAC protocol called the Virtual Sensing Directional Hub Medium Access Control (VSDH-MAC) protocol, which employs an original approach to implementing random access techniques, designed to improve the channel capacity with spatial reuse and selective backoff strategy, reducing collisions with virtual channel sensing and node energy consumption with a power control strategy. While in most instances the DMAC protocols assume idealised directional antenna patterns, the VSDH-MAC protocol incorporates realistic directional antenna patterns to deliver enhanced link performance. The ideas and concepts employed by this protocol originate through consideration of how to effectively reduce collisions, given some applications of WSN where synchronisation and coordination between users/nodes are not supported. VSDH-

MAC has been subjected to significant development and analysis, and a modified variant of VSDH-MAC is also presented. The VSDH-MAC protocols have successfully provided solutions to some traditional challenges to random access techniques, providing enhanced throughput performance with reduced energy consumption at each sensor node, compared to the case with only omni-directional antennas and other DMAC protocols. The novel concepts and contributions introduced in this chapter have resulted in the following publication [120].

VSDH-MAC is introduced in Section 7.2, along with the power control and selective backoff strategy employed. A detailed description of the functionality and operation of the protocol is given, followed by a description of the simulation model and performance evaluation in Section 7.3, based on a combination of graphical and mathematical analysis. The simulated performance is then compared with a suitable variant of protocols developed by other researchers, based on a combination of contention-based protocols and directional antennas in Chapter 3. Different antenna patterns are applied to VSDH-MAC in Section 7.3 to investigate the effects of the application of different antenna patterns. Section 7.4 presents a variant of VSDH-MAC protocol where an additional sensing procedure is introduced, followed by a detailed performance evaluation. This chapter ends with a summary in Section 7.5.

7.2 Virtual Sensing Directional Hub MAC Protocol

A key challenging aspect of the directional MAC protocol considered in this chapter is the antenna pattern of the directional antenna. While most previous research has focused on the link performance provided by the MAC protocols, a number of simplifying assumptions are made with no regards on the directional antenna pattern, energy consumption, and other limitations such as sensor nodes complexity and positioning capability [93, 113, 121-128]. In terms of selection of suitable MAC protocols for WSNs, one could consider either contention-based or contention-free protocols. Contention-based protocols can be less efficient than those without contention in terms of throughput performance for large star topologies due to the number of collisions when the data traffic offered load is high. However, they are simpler and typically provide lower delay in smaller WSNs [129]. Contention-based protocols are a promising approach for DMAC protocols, as they enable multiple sensor nodes to simultaneously access a channel without the need for synchronisation. Scheduling and synchronisation are the main challenges for contention-free protocols, especially for WSNs with mobile nodes and/or a varying number of nodes. In this chapter, a modified directional Carrier Sense Multiple Access with Collison Avoidance (CSMA/CA) protocol for wireless sensor networks (WSNs) is proposed, which is similar to the IEEE 802.11 Wi-Fi standard and the IEEE 802.15.4 standard for WSNs. The traditional physical carrier sensing is not used to reduce sensor node energy consumption. Here a virtual carrier sensing process is performed via handshaking packets instead. A version with physical carrier sensing similar to the CSMA/CA protocol is also considered for comparison. The hub node is equipped with multiple directional antennas, and the channel is efficiently utilised through the benefits of spatial reuse. A dynamic transmit power control algorithm and a selective backoff strategy is employed at the sensor nodes to improve the sensor node energy efficiency, fairness and end-to-end delay. A uniform signal-to-interference-plus-noise ratio (SINR) is achieved for packets from all sensor nodes in the network.

7.2.1 VSDH-MAC Description

The proposed VSDH-MAC protocol is similar to that of IEEE 802.11 DCF (Distributed Coordination Function), which uses the CSMA/CA/DCF protocol [52], and the IEEE 802.15.4 protocol which is a CSMA/CA protocol. However, continuous physical channel sensing is not performed. Instead, virtual channel sensing is enabled using Request-to-send / Clear-to-Send (RTS/CTS) packets in a similar way to the CSMA/CA/DCF protocol. The packet exchange procedure of the VSDH-MAC protocol follows the IEEE 802.11 CSMA/CA/DCF method with the RTS/CTS and Data / Acknowledgement (DATA/ACK) structure as shown in Figure 7.1. This distinctions between the IEEE 802.11 DCF and the VSDH-MAC are the use of directional antennas, the virtual carrier sense instead of the physical carrier sense, the selective backoff strategy, and the dynamic transmit power control strategy. The analytical models developed for IEEE 802.11n/ac/ad MAC protocol cannot be directly applied to the VDSH-MAC protocol due to the use of different frequency channels and hybrid access methods. The IEEE 802.11n/ac/ad are also not appropriate for WSN applications as they are designed for high data rate and short range communication applications such as mobile phones.

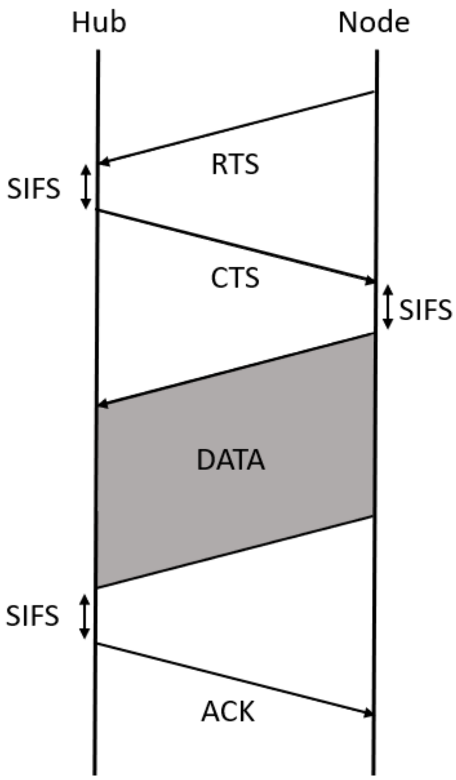

Figure 7.1. Uplink and downlink frame formats of VSDH-MAC.

When a sensor node has no data packet to transmit, i.e. its packet queue is empty, it will remain in a sleep state to conserve energy. When a sensor node wishes to transmit a data packet, it will start by sending a short RTS packet to the hub immediately, with its maximum transmit power. The maximum transmit power is used for RTS packet because it is assumed that sensor nodes might move, as might the obstacles and interferers, and the RTS packets are required to reach the hub regardless of the current node position, which is assumed to be unknown. All RTS packets are transmitted on a best effort basis, with the packet inter-arrival time exponentially distributed. It is assumed that a node cannot send and receive at the same time since the hardware would have prevented it. If the sensor node receives a CTS packet from the hub node, in response to the RTS packet within a limited time duration, it may then transmit the data packet to the hub. This protocol incorporates a transmit power control strategy for its data transmission. Sensor nodes are assumed to know the hub transmit power as the hub node transmit all packets with a constant transmit power. The received power of the CTS packet at the sensor node is then used to compute the path loss and thereby choose the least required packet transmit power to successfully transmit the data packet, assuming a reciprocal channel. This is done in order to minimise both the interference to other nodes and the sensor node power consumption. Although it is of course simple to introduce an appropriate link margin by increasing the transmit power above the calculated minimum if desired, to account for uncertainties and variation in the channel, e.g. due to shadowing. As stated in Chapter 4, the same background noise is assumed at both the transmitter and the receiver. In a real network, while the reciprocal path is the same, the background noise might not be. Hence, in a practical protocol, it would be necessary for the hub to calculate the required transmit power with its background noise and include the value in the CTS as a reference for the sensor node. Different from the DH-Aloha-PC protocol in Chapter 6, the dynamic transmit power adjustment using the RTS/CTS exchange reduces the time difference between the packet received and the packet transmission. This provides a more reliable transmit power estimation to account for uncertainties and variation in challenging wireless environments, i.e. due to shadowing or sensor nodes mobility. RTS and CTS packets both contain a network allocation vector (NAV) which defines the time required to complete the subsequent data packet transmission and associated handshaking. Other sensor nodes overhearing a CTS above certain amplitude threshold will delay their transmission to avoid collision. This is further discussed in Section 7.2.2. In order to conserve energy, sensor nodes only listen to the channel during the time they are waiting for a reply to their own packets. This maximises the chance of avoiding collisions between active nodes whilst minimizing node energy consumption as a node does not need to listen to the channel unless it is likely to be transmitting data. The timeout duration is defined as the propagation time of the packets, aka the round trip time (RTT), and a Short InterFrame Space (SIFS) duration. For example, node will listen to the channel for the duration of:

$$T_{S\_RTS} = T_p + T_{SIFS} + T_{CTS} \tag{7.1}$$

where T_p is the propagation time of the packet, T_{SIFS} denote the duration of SIFS time and T_{CTS} is the time required transmit the CTS packet.

Operation of the protocol at the hub node is slightly more complex as it has multiple antennas and corresponding transceivers. The hub is assumed to be capable of communicating on all directional antennas simultaneously and listening continuously on any antenna that is not transmitting (HDX on each antenna). If the hub receives an RTS message from the same node on one or more antennas, it will note which antenna had the highest signal-to-interference-plus-ratio (SINR). This antenna will be used for subsequent communications with that node until a packet arrives at a different antenna with a higher SINR from the same node. It is assumed that the hub node will not initiate a transmission to the sensor nodes. Upon receiving a RTS from any node, and no other RTS being received by this antenna (not reserved), the hub will reserve this antenna for a period indicated in the RTS (NAV) and transmit a CTS to the source node using this antenna. If the hub node receives an RTS on more than one antenna, the antenna with the highest SINR will be selected as the optimum antenna and will be reserved for the node with a CTS transmission. The CTS packet also contains a NAV which will cause any listening node to delay its transmission, if the received SINR is above a certain threshold. As nodes do not continuously listen to the channel, there is still a probability of collision by a node that does not hear the ongoing exchange when it is ready to transmit.

7.2.2 Selective Backoff Strategy

The backoff stage is activated at the sensor nodes selectively, based on the received signal strength (RSS) of the overheard CTS packets. Only the sensor nodes receiving the CTS with the RSS above the threshold will enter the backoff stage. The threshold is defined as the product of the packet transmit power and the receiving antenna gain at angle θ (G_θ), where $\theta = \frac{360}{M}$, and M is denoted as the number of directional antennas at the hub. Nodes can only listen for a CTS during the time when they are awaiting a reply for their own RTS. If the sensor node receives no response to it RTS within the timeout duration, it will enter a backoff state, in which transmission of another RTS for the same data is delayed by a random delay in the range of $[0, CW - 1]$, where CW is an interval called the Contention Window. Subsequent failures to receive a CTS increase the backoff duration range exponentially by a factor of 2 in each case. The value of the random backoff interval is chosen from the CW, which lies between two preconfigured values, CW_min and CW_{max}. The values for these are identical to the binary exponential backoff (BEB) in the IEEE 802.11 CSMA/CA/DCF protocol. The contention window is set to CW_min at the first transmission attempt for each data packet, and doubles after each unsuccessful attempt, until it reaches CW_max. The contention window is reset to CW_min after every successful transmission. After the counter reaches CW_max the packet transmission would be abandoned, and the error would also be reported to the layer above. Once a packet is transmitted, if an acknowledgement is not received within the specified RTT time for the data packet, a retransmission with maximum transmission power for the data packet will be performed following the same RTS/CTS/DATA/ACK sequence. Thus, the sensor node protocol is designed to require minimal electrical and processing power.

On the other hand, if the sensor node overhears a CTS packet destined for another sensor node after transmitting its RTS packet, it will defer its transmission by the NAV data within the CTS packet to avoid collision if the received signal strength (RSS) of the CTS packet is above the threshold. This is then followed by the BEB before the sensor node attempts another transmission. The RSS value of the CTS packet allows the sensor node to determine whether the CTS packet is destined for a sensor node within its antenna sector, in order to decide if backoff is required. If the RSS is below the threshold, it indicates that a directional antenna is being reserved by a sensor node, located in another antenna sector. The interference caused by the transmission from this sensor node will not cause a collision since the SINR will be sufficient. Hence, the sensor node does not need to enter the backoff state. As a result, the effect of the exposed node problem can be reduced, as well as end-to-end delay and unused channel capacity caused by the unnecessary backoff.

7.2.3 Power Control Strategy

Since sensor nodes are free to move independently, the transmit power of the sensor nodes must be allocated dynamically to ensure sufficient SINR for each data packet. Therefore, a SINR-based power control strategy with directional antennas is used for interference measurement. It is assumed that sensor nodes are equipped with an omni-directional antenna to reduce hardware complexity. In order to ensure successful handshaking, sensor nodes will send the RTS packets with its maximum transmit power. Extensive simulations implemented in Riverbed Modeler have shown that although the RTS packets are sent with maximum power, there is no significant impact to the sensor node energy consumption and overall network throughput. The CTS packet transmitted from the hub node following a successful RTS reception will be used for power management and channel reservation. The sensor node measures the current interference in the radio environment using the handshaking packets. The sensor node calculates the required power for a successful transmission using the received power of the CTS by assuming a reciprocal path and knowledge of the hub transmit power. The received power of the CTS packet P_{rx_CTS} can be expressed as:

$$P_{rx\_CTS} = \frac{P_{tx\_CTS}\, G_{node}\, G_{hub}\, \lambda^2}{(4\, \pi\, r\,)^2} \tag{7.2}$$

where P_{tx_CTS} is the transmit power of the CTS packet, G_{node} and G_{hub} are the antenna gain of the hub and node antennas, λ is the wavelength and r is the propagation distance between the antennas. Nodes can then calculate the antenna gain of the hub antenna as:

$$G_{hub} = \frac{P_{rx\_CTS}\, (4\, \pi\, r\,)^2}{P_{tx\_CTS}\, G_{node}\ \lambda^2} \tag{7.3}$$

Finally, the required transmission power for the data packet P_{tx_DATA} can be derived by:

$$P_{tx\_DATA} = \frac{P_{rx\_CTS}\, (4\, \pi\, r\,)^2}{G_{node}\, G_{hub}\, \lambda^2} \tag{7.4}$$

Algorithm 2 VSDH-MAC protocol with power control algorithm. cd_CW is the number of contention window, cd_RTS, cd_DATA are counters for sensor nodes after transmitting RTS and DATA packets respectively, cd_NAV is a counter based on the NAV from the overheard packet, CW_max is the maximum value for contention window.

```
for each packet arriving queue do
   while cd_CW = 0 do
      if ongoing transmission = 0 then
         Send RTS to receiver
         Start countdown timer (cd_RTS)
         if CTS received && cd_RTS > 0 then
            update P_tx based on the CTS received power
            Send DATA to receiver
            Start countdown timer (cd_DATA)
            if ACK received && cd_DATA > 0 then
               Packet transmission successful
            else
               Update P_tx to maximum
         else if CTS for other nodes received && cd_RTS > 0 then
            Update cd_NAV based on overhead CTS
            cd_CW = a random CW value (where CW = [ 0, CW_max – 1]
            Start countdown timer (cd_CW = cd_NAV + cd_CW)
         else
            Update P_tx to maximum
            cd_CW = a random CW value (where CW = [ 0, CW_max – 1]
            Start countdown timer (cd_CW)
         end if
      end if
   end while
end for
```

A dynamic transmit power is crucial since interference may change; thus, the power assigned to ensure the packet delivery may be insufficient in some cases, i.e. at high sensor node mobility. The effects of sensor node mobility on throughput performance is presented later in this chapter.

7.3 Simulation Model and Performance Evaluation

7.3.1 Overview

To fairly characterise the performance of the protocols, a series of randomly generated configurations with the simulation parameters outlined in Table 7.1 are considered. Note that the SIFS and BPSK in Table 1 stands for Short Interframe Space and Binary Phase Shift Keying respectively. The purpose of this set of results is to present the performance of the VSDH-MAC protocol, show how different features of a WSN can benefit from the using virtual channel sensing instead of physical channel sensing, and investigate the performance improvements that can be achieved using it in terms of the QoS provided to the sensor nodes. A single hop star topology with HDX operation on a single frequency has been chosen as this is simple and common in WSNs. A HDX operation is defined as a system supporting communication in both directions, but only one direction at a time. The star topology allows for a continuously powered hub where energy usage and complexity are not considered to be an issue. 10 static and 10 mobile simulation models with different topologies have been developed using Riverbed Modeler, enabling effective and accurate performance comparison of the VSDH-MAC variants with other directional MAC protocols. Three directional MAC protocols have been replicated for the purpose of performance comparison. All protocols are implemented with the same simulation parameters and the same sets of network topologies. These protocols include the directional CSMA/CA protocol [88], the Directional Virtual Carrier Sensing MAC (DMAC) protocol [89], and the Cooperative Multichannel Directional MAC (CMDMAC) protocol [94]. The detail descriptions of these protocols can be found in Chapter 3. These protocols operate with similar channel sensing techniques modified from the basic IEEE 802.11 CSMA/CA protocol, in which sensor nodes perform continuous channel sensing to avoid collisions to improve throughput performance.

Table 7.1 Simulation parameters for VSDH-MAC.

Parameters	Values
Frequency band	2.4 GHz
Channel bit rate	250 Kbit/s
RTS, CTS, ACK length	8 bits
Data length	1024 bits
Number of Hub Antennas (M)	4
Maximum Transmission Power	0.05 W
Node Received Power	0.03 W
Node Sleep Power	0.01 mW
Digital modulation	BPSK
CW_min	31
CW_max	1023
SIFS	10 us

The directional antenna patterns presented in Chapter 4 are employed for the performance comparison. In all simulations, free space propagation is considered as an illustrative example. Similar to the simulations in the previous chapters, the SINR is used to determine the BER. The data packets are generated according to a Poisson Process with a rate (G), which is referred as the channel traffic offered load. The Poisson arrival process gives an exponential distribution interarrival time of the data packet generation. Four hub antennas is chosen as a reasonably practical number to illustrate the performance of a multi-antenna hub. Fewer hub antennas could be used with little effort. However, if a significant increase in the number of antennas were required, the issue of beam overlap may become a significant problem. Some overlap is necessary in any practical system as it is not possible to design antennas with ideal cut off at the beam edges, but as described in Chapter 5, beam overlap is a significant factor in limiting the throughput performance.

7.3.2 Lifetime Estimation

Some WSN applications are sensitive to the energy consumption of the sensor nodes, due to the restricted physical resources of the sensor nodes. One of the advantages of using power control and virtual sensing instead of physical sensing is that it reduces the overall sensor node energy consumption and the potential to extend the lifetime of the wireless sensor node. This sub section demonstrates these potential lifetime enhancements achieved by the VSDH-MAC protocol. First, the energy consumption during the data transmission reception and control packets is given. Second, the energy consumed per successful bit is split to show the breakdowns of average energy consumption in different states. Thirdly, the lifetime estimation of the sensor nodes provided.

Successful data packet transmission (E_{tx}):

$$E_{tx} = P_{tx_{RTS}} T_{RTS} + P_{tx_{DATA}} T_{DATA} + P_{rx} \left(T_{CTS} + T_{ACK} + 2\ x\ T_p + T_{SIFS}\right) \quad (7.5)$$

Colliding RTS or CTS transmission (E_{c_RTS}):

$$E_{c\_RTS} = P_{tx_{RTS}} T_{RTS} + P_{rx} \left(T_{CTS} + T_p\right) \quad (7.6)$$

Colliding DATA or ACK transmission (E_{c_DATA}):

$$E_{c\_DATA} = P_{tx_{DATA}} T_{DATA} + P_{rx} \left(T_{ACK} + T_p + T_{SIFS}\right) \quad (7.7)$$

Backoff due to unsuccessful RTS/CTS communication (E_{BO}):

$$E_{BO} = P_{sleep} \left(T_{CW}\right) \quad (7.8)$$

Overhearing reception destined to other user after RTS transmission, (E_{OH}):

$$E_{OH} = P_{rx} \left(T_{SIFS}\right) + P_{sleep} \left(T_{NAV} + T_{CW}\right) \quad (7.9)$$

Sleep when no packet transmission is required (E_{sleep}):

$$E_{Sleep} = P_{Sleep} T_{Sleep} \quad (7.10)$$

In addition, when carrier (DIFS) sensing is used, additional energy (E_{DIFS}) is consumed:

$$E_{DIFS} = P_{rx} T_{DIFS} \quad (7.11)$$

where T_{DIFS} is the time during which the carrier is sensed. If a transmission is detected during T_{DIFS} then additional energy is expended (E_{OH_DIFS}) whilst the sensor node waits before attempting to transmit again:

$$E_{OH\_DIFS} = E_{DIFS} + P_{sleep} \left(T_{NAV} + T_{CW}\right) \quad (7.12)$$

where, P_{sleep}, $P_{tx_{RTS}}$, $P_{tx_{DATA}}$, and P_{rx} are the power consumed in sleep, transmit and receive mode respectively. T_{SIFS}, T_{DIFS} and T_P are the SIFS and DIFS time durations from the IEEE 802.11 DCF standard and the propagation time of the packet. T_{CW} is the backoff time duration. T_{RTS}, T_{CTS}, T_{DATA}, and T_{ACK} denotes the packet transmission time for RTS, CTS, DATA, and ACK packets respectively. T_{sleep} is the time for the node to stay in the sleep state. T_{NAV} represents the backoff time indicated from the received NAV.

Figure 7.2 shows a plot of the breakdown of the average energy consumption per successful data bit in a sensor node, with respect to the channel offered load. Figure 7.2(a) is the energy consumption of the VSDH-MAC protocol with power control strategy. Figure 7.3(b) is the energy consumption of the VSDH-MAC protocol without the power control strategy. Figure 3(c) is the energy consumption of the directional IEEE 802.11 DCF protocol. Table 7.2 shows the operational states of the sensor node with the power consumption of each state. By comparing those figures, it can be seen that the VSDH-MAC protocol provides a far higher energy efficiency than CSMA/CA protocol.

Table 7.2. Operational States for FSM of Sensor Nodes

State	Activity	Tx	Rx	Power Required
S_0	Sleep	Off	Off	0.462 mW
S_1	RTS Tx	On	Off	10 mW
S_2	Receiving	Off	On	3 mW
S_3	Data Tx	On	Off	5 mW (Average)

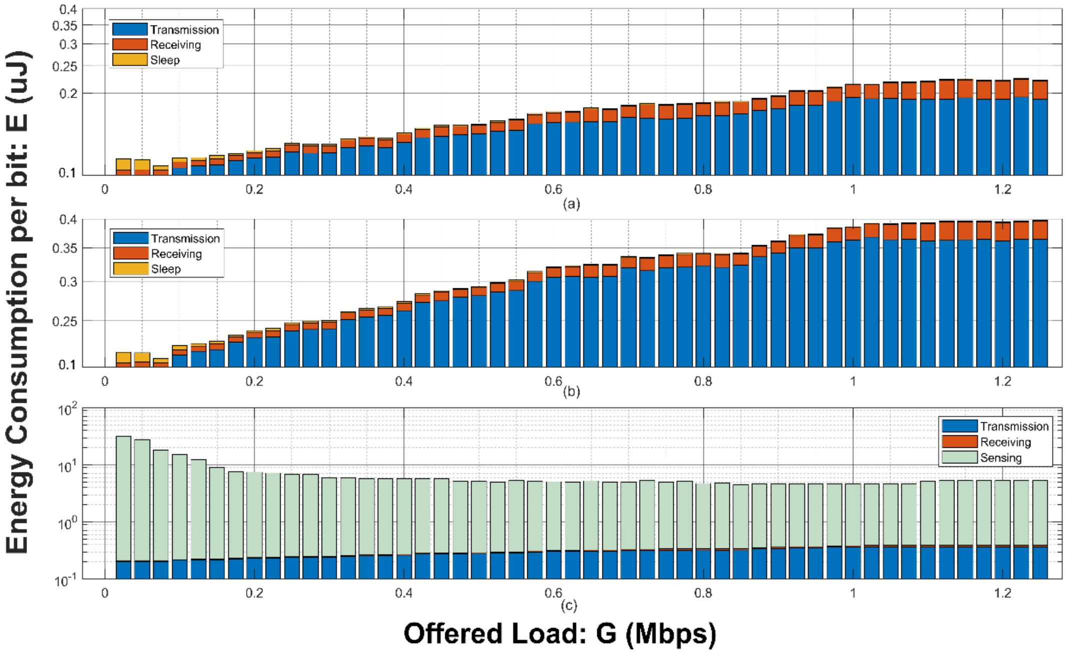

Figure 7.2. The comparison of the required transmission energy per bit for VSDH-MAC with power control (a), and without power control (b), and the directional CSMA/CA/DCF protocol (c).

Figure 7.3 shows the average transmission energy required by the VSDH-MAC protocol with and without power control, for each successful data bit. It demonstrates that the power control strategy can effectively reduce the average required transmission energy by a factor of 2. Since one of the goals of the VSDH-MAC is to prolong the lifetime of the sensor node and hence the network lifetime. It is therefore worth investigating the performance of the VSDH-MAC protocol with quoted values from a real wireless sensor node. To quantitatively compare the lifetime estimation of the VSDH-MAC against other directional MAC protocols, quoted values from the MICAz mote [22] are adopted. Two 1.5V batteries rated at 2000 mAh each are assumed for each sensor node, in which the current draw and the size of the packets are assumed to be fixed. Figure 7.4 shows the numerical comparison of the expected lifetime obtained from the directional MAC protocols.

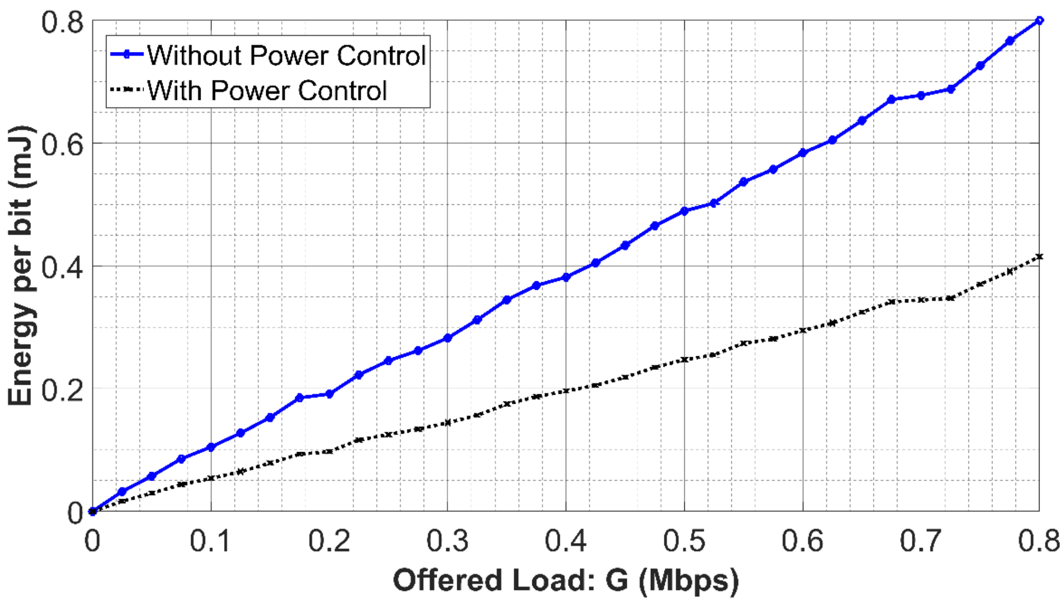

Figure 7.3. The required transmission energy per bit with and without the power control scheme.

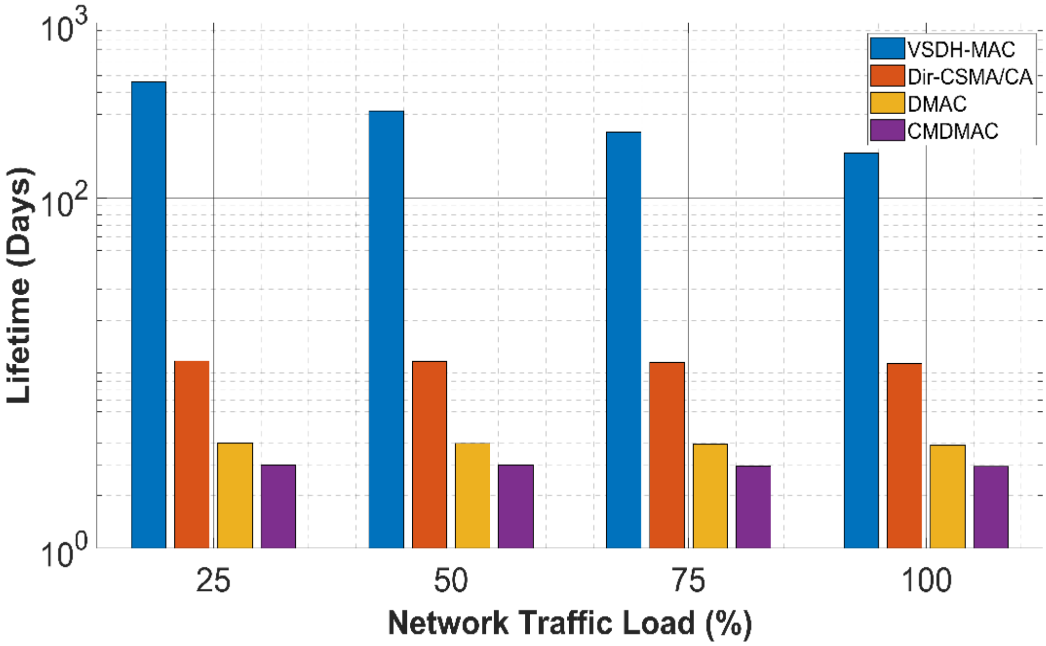

Figure 7.4. The comparison of the expected sensor node lifetime with different network traffic offered load.

Figure 7.3 and Figure 7.4 highlight that the VSDH-MAC protocol exhibits superior energy efficiency and lifetime expectancy compared with other directional MAC protocols at various traffic loads. Compared to the VSDH-MAC protocol, the other directional MAC protocols suffer from the significant amount of energy consumption from the physical carrier sensing, with a major reduction in the lifetime expectancy. This mechanism with the lack of transmit power control further reduce the lifetime of the sensor nodes. It is therefore important to have an accurate energy model and lifetime estimation of a sensor node, as the lifetime of a WSN is dependent on it.

7.3.3 Effects of the Virtual Channel Sensing

Figure 7.5 shows the comparison of the mean throughput performance of the VSDH-MAC protocol as a function of the channel traffic offered load. Here, the throughput and traffic offered load are measured in bits per second (bps) instead of Erlangs.

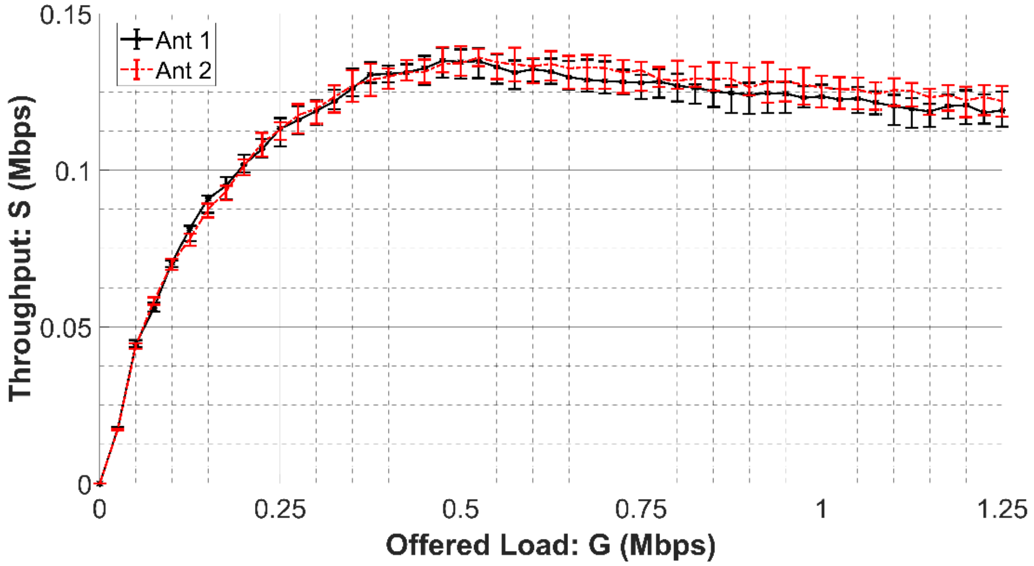

Figure 7.5. The comparison of throughput performance of VSDH-MAC protocol with different antennas.

As the traffic offered load is increased, the mean throughput performance is increased until it reaches a channel load of 50% (0.5 Mbps). The mean throughput performance becomes stable above the channel load of 50%, since the number of packets successfully reached saturation due to the limitations of the antenna pattern. Compared to the throughput performance of the DH-Aloha protocol from Chapter 5 and Chapter 6, the difference between the two antennas are significantly smaller. This is because the power control mechanism during the RTS/CTS handshaking reduces the effect of the antenna overlap by adjusting the sensor node transmission power. The adjusted transmission power reduces the interference caused by the side and back lobes. In general, the mean throughput performance is much more stable at higher offered loads, compared to DH-Aloha where the mean throughput performance decreases as the offered load increases past the optimal point. The reason for this is because a larger proportion of packet collisions are avoided with the handshaking mechanism, and this therefore increases the useful throughput when there are a greater number of sensor nodes attempting to access the channel.

It is useful to compare the throughput performance of the VSDH-MAC protocol with other directional MAC protocols. Figure 7.6 shows the maximum throughput achieved with an idealised directional antenna pattern is significantly higher than using realistic antenna patterns. It is also worth noting that the throughput difference between Ant 1 and Ant 2 for DMAC and CMDMAC are due to different degrees of overlap caused by the antenna pattern. However, this is carefully addressed by the power control strategy described in section 7.2.3.

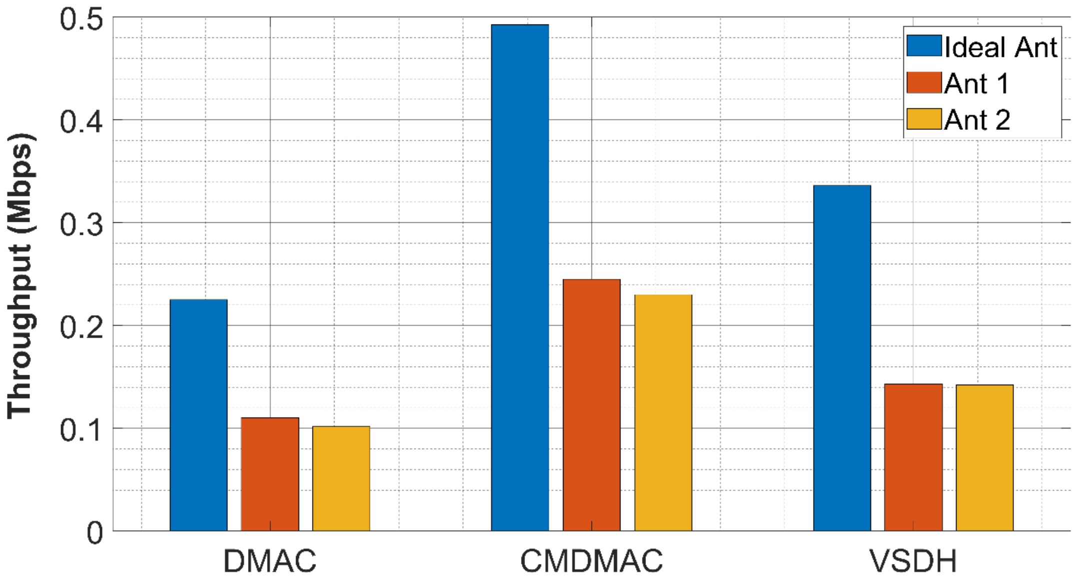

Figure 7.6. The impact of antenna patterns on throughput performance.

For directional MAC protocols, the throughput performance of the schemes is heavily dependent on the antenna patterns. With an idealised antenna, the maximum throughput can be around twice greater than with the realistic antenna patterns Ant1 and Ant2. Both directional MAC protocols, the DMAC and the CMDMAC are replicated with the parameters described in Table 7.1. However, the sensor nodes in the DMAC protocol require a directional antenna and Global Positioning System (GPS), and the CMDMAC protocol require each sensor node to be equipped with an omni-directional antenna for handshaking communications such as RTS/CTS, and a directional antenna for data transmission on a separate channel. Since both protocols are modified from the IEEE 802.11 CSMA/CA/DCF protocol, sensor nodes are required to perform continuous channel sensing. The using of the extra hardware and the channel sensing have significantly increased the sensor node energy consumption for these protocols. Although the CMDMAC protocol might provide better throughput performance, under these conditions, the additional requirements mean that the throughput performance comes at the cost of increased sensor node manufacturing cost, energy consumption and end-to-end delay.

Figure 7.7 shows the mean end-to-end delay as a function of the traffic offered load for the VSDH-MAC protocol and a direcctional CSMA/CA/DCF protocol, in which the sensor nodes are equipped with an omni-directional antenna and the hub node is equipped with four directional antennas. At low traffic loads, the CSMA/CA/DCF protocol suffers from the exposed node problem, where transmision in another antenna sector can cause unnecessary backoff during channel sensing procedure. This is the main source of delay for the directional CSMA/CA/DCF protocol until the offered load is higher and suffer more delays due to the backoff causing queue building up. On the other hand, the VSDH-MAC protocol does not suffer from these problems. Since the dynamic backoff strategy minimises the exposed node problem, the VSDH-MAC protocol has a much lower end-to-end delay compared with the directional CSMA/CA/DCF protocol, with a slight increase at higher traffic offered load. Selective backoff becomes less effective as the traffic offered load increases, with slightly poorer performance when the number of devices transmitting at each antenna sector increases.

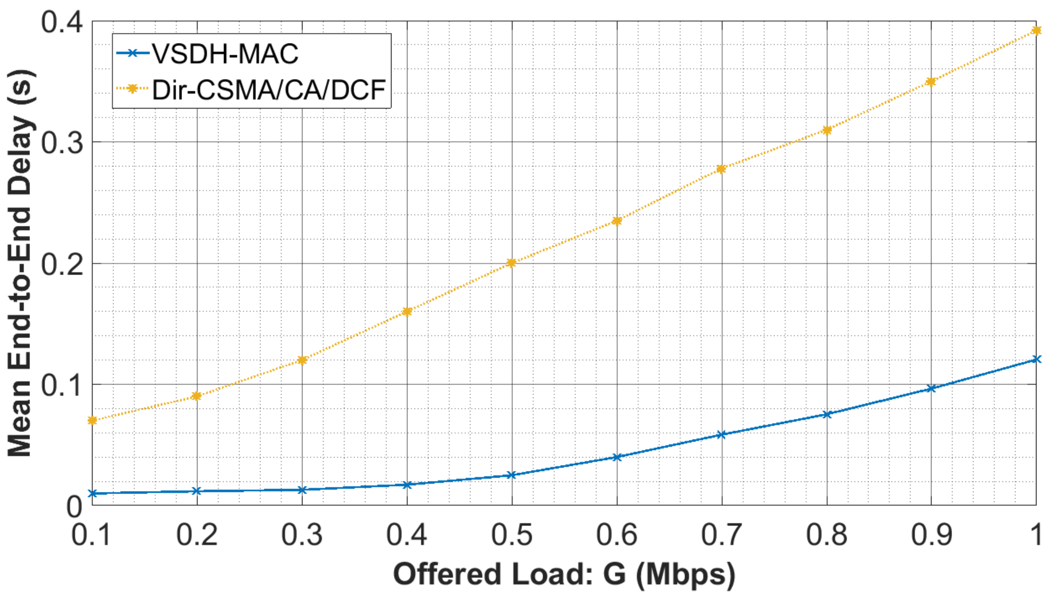

Figure 7.7. Mean end-to-end delay performance as a function of traffic offered load.

In Figure 7.8 the impact of the transmission distance on fairness performance and the effect of power control strategy is depicted. The simulations have been performed under 100% traffic offered load, when the throughput has reached the saturation point, the same set of topologies used for the throughput depicted in Figure 7.5. Heavy traffic offered load conditions are more likely to be of interest in evaluating fairness since at lower load conditions, fairness may not be an issue with fewer contending sensor nodes. It can be seen that the effect of distance on the throughput performance is much less with the power control strategy, thus increasing the fairness of the network. In wireless communication, increasing the propagation distance would increase the path loss in the transmission, which will cause the SINR to decrease. However, the power control strategy in the VSDH-MAC protocol provides a uniform SINR for all sensor nodes regardless of the propagation distance, thus increasing the per node fairness.

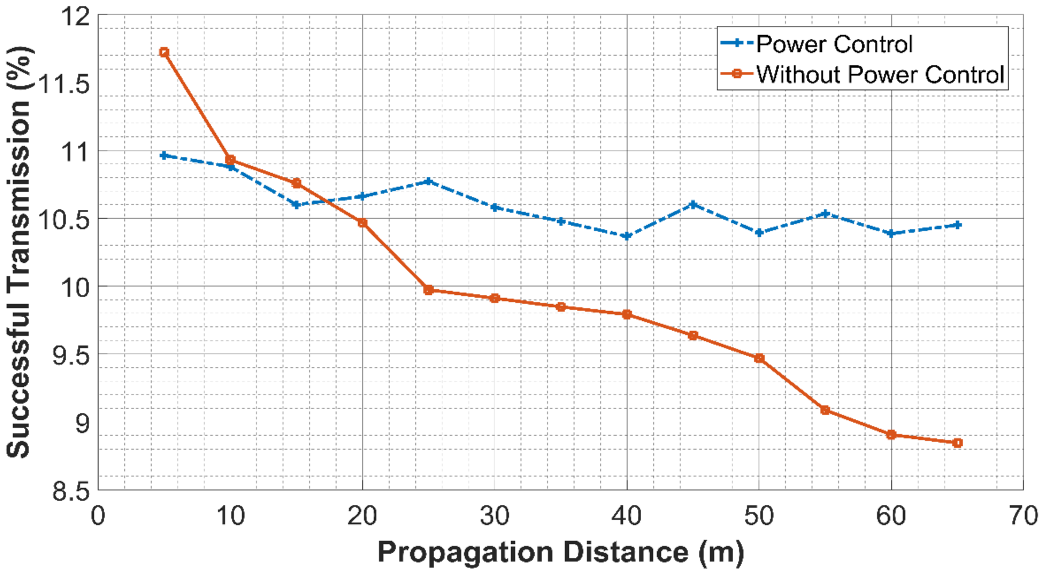

Figure 7.8. The proportion successful transmissions as a function of distance from the hub at maximum traffic offered load.

Figure 7.9 compares the fairness performance of the VSDH-MAC protocol and the directional IEEE 802.11 CSMA/CA/DCF protocol using Jain's fairness index, as a function of the network traffic offered load. It indicates that the VSDH-MACA protocol with the power control strategy achieves a higher and more consistent fairness index than the case without power control and the directional CSMA/CA. Since the CSMA/CA protocol is a random access scheme with backoff, it suffers from low fairness performance. Due to the inherent exponential backoff mechanism, when a sensor node fails to acquire the channel, it will double its backoff window. At higher offered load values, the value of the Jain's fairness index decreases, as more sensor nodes try to gain access at a given time and some sensor nodes are forced into backoff. Once a sensor node is able to transmit a packet, it will have a much better probability of getting access to the channel again than other sensor nodes who might have backoff waiting periods. On the other hand, the combination of selective backoff and power control strategy using the CTS SINR threshold reduces the number of nodes entering backoff, allowing a high level of fairness. This is supported by the results in Figure 7.9, which it indicates that all sensor nodes within the network have an equal opportunity to transmit a packet to the hub and of being received successfully.

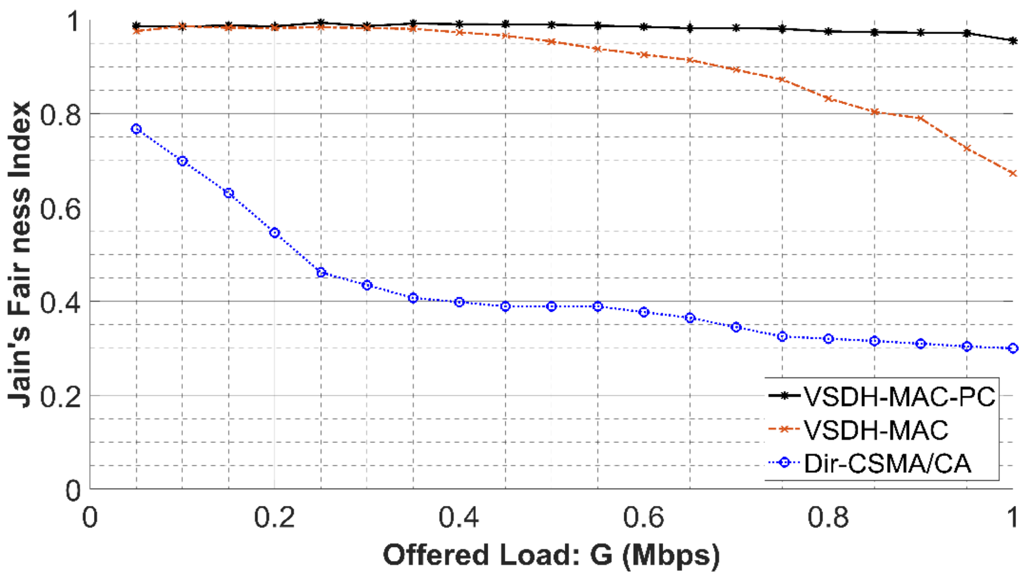

Figure 7.9. Jain's fairness index improvements with the power control mechanism applied compared to VSDH-MAC with no power control and directional CSMA/CA in a WSN with 50 sensor nodes.

7.3.4 Mobile Scenario

In the previous section, the throughput performance was evaluated as a function of the traffic offered load for a selection of static network scenarios. The results provided an insight into the effectiveness of the control packet handshaking and the power control strategy in reducing packet collisions and antenna pattern overlap. An alternative approach is to observe the performance of the VSDH-MAC protocol under mobile scenarios in detail. In this extended study of the VSDH-MAC, sensor nodes moving at a pre-defined constant velocity throughout each simulation. The hub node remains stationary, but the sensor nodes will move towards a set of random coordinates with the network area during the simulations. Table 7.2 gives the parameters relevant to the simulation performance evaluation of the mobile VSDH-MAC. The movement path for sensor node 1 and sensor node 10 have been shown in Figure 7.10 as an example.

Table 7.3 Simulation parameters for VSDH-MAC in Mobile Scenarios

Parameters	Values
Frequency band	2.4 GHz
Channel bit rate	250 Kbit/s
RTS, CTS, ACK length	8 bits
Data length	1024 bits
Maximum Transmission Power	0.05 W
Node Received Power	0.03 W
Node Sleep Power	0.01 mW
Digital modulation	BPSK
CW_min	31
CW_max	1023
SIFS	10 us
Sensor Node Velocity	2, 5, 10, 20, 40 mile/hour

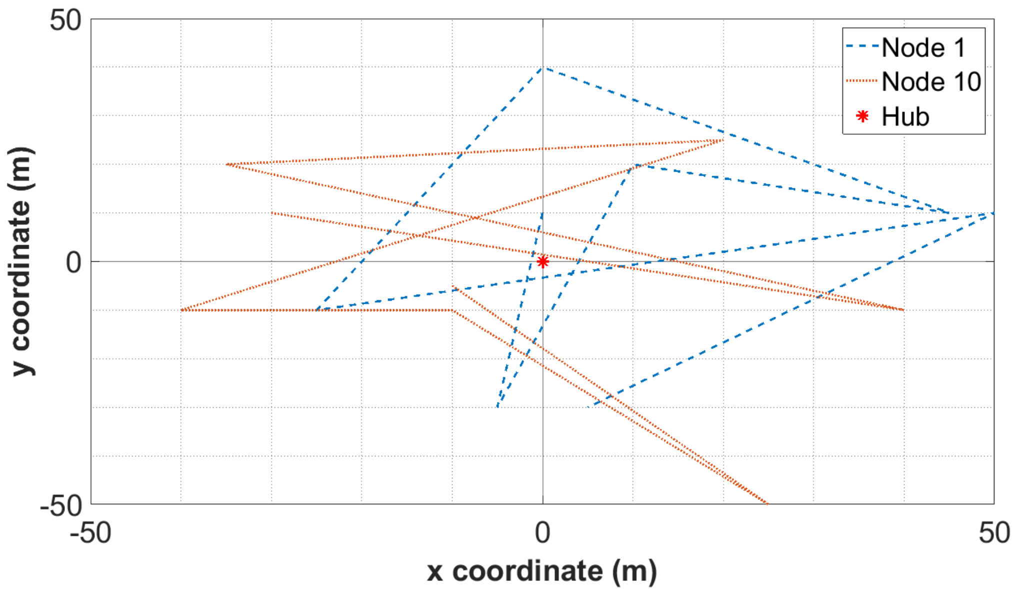

Figure 7.10. Example movement path of sensor nodes in mobile scenarios.

The throughput discrepancy of mobile scenarios over static scenarios is presented in Figure 7.11. At low sensor node velocity between $0 - 5\ mi/hr$, the throughput performance is similar to the throughput performance of a static network, as all packets are transmitted and received before the received antenna gain and SINR of the packet changed drastically. With the increased sensor node velocity, the throughput performance of the network remains similar to the static network at low offered load, between $0 - 50\%$ traffic offered load. As the channel is less busy at lower load conditions, the probability of multiple sensor nodes contenting for channel access is lower, hence the impact on the SINR is less significant. However, under heavy load conditions, a larger proportion of the packets with a lower SINR will be interfered due to the increased number of transmitting nodes, resulting in a higher number of packet loss and hence the high discrepancy in throughput performance.

Figure 7.11. The mean throughput discrepancy of VSDH-MAC in mobile scenarios at different node velocity as a function of traffic offered load over static scenario.

7.4 VSDH-MAC Variant – Additional Sensing VSDH-MAC

7.4.1 Introduction

The results presented in Section 7.3 imply that a combined protocol, drawing on the advantages of both the directional antenna and the contention-based random access technique may result in improved performance in terms of throughput, energy consumption and fairness. A new variant of the VSDH-MAC protocol has been developed which provides additional channel sensing to the protocol.

The simplest possible implementation of this variant protocol to VSDH-MAC is to allow sensor nodes to perform a short period of channel sensing prior to RTS/CTS control packet handshaking. It has been found that combining these strategies results in similar energy performance to the VSDH-MAC, but with some significant improvements in the network throughput performance.

Algorithm 3 VSDH-MAC protocol with additional sensing. cd_CW is the number of contention window, cd_RTS, cd_DATA are counters for sensor nodes after transmitting RTS and DATA packets respectively, cd_NAV is a counter based on the NAV from the overheard packet, CW_max is the maximum value for contention window.

```
for each packet arriving queue do
   while cd_CW = 0 do
      if ongoing transmission = 0 then
         Start countdown timer (cd_DIFS)
         while counter (cd_DIFS) > 0
             if CTS detected && cd_DIFS > 0 do
               Pause counter (cd_DIFS)
               Update cd_NAV based on overhead CTS
               cd_CW = a random CW value (where CW = [ 0, CW_max – 1]
               Start countdown timer (cd_CW = cd_NAV + cd_CW)
             end if
         restart counter (cd_DIFS)
         Send RTS to receiver
         Start countdown timer (cd_RTS)
         if CTS received && cd_RTS > 0 then
            update P_tx based on the CTS received power
            Send DATA to receiver
            Start countdown timer (cd_DATA)
            if ACK received && cd_DATA > 0 then
               Packet transmission successful
            else
               Update P_tx to maximum
         else if CTS for other nodes received && cd_RTS >0 then
            Update cd_NAV based on overhead CTS
            cd_CW = a random CW value (where CW = [ 0, CW_max – 1]
            Start countdown timer (cd_CW = cd_NAV + cd_CW)
         else
            Update P_tx to maximum
            cd_CW = a random CW value (where CW = [ 0, CW_max – 1]
            Start countdown timer (cd_CW)
         end if
      end if
   end while
end for
```

The additional sensing employed by the DIFS-VSDH-MAC scheme reduces the collision of the RTS/CTS control packets. Access to the channel via the RTS packet is limited to sensor nodes that have sensed the channel to be freed for a DCF Interframe Space (DIFS) period. Similar to the selective backoff strategy employed in the VSDH-MAC scheme, the sensor node would only pause the DIFS counter if a CTS packet is received above the SINR threshold. The duration of the pause is based on the NAV in the CTS packet. The sensor node will continue with the countdown at the end of the NAV. Different to the CSMA/CA/DCF protocol, when the channel is sensed busy during the DIFS period, the sensor node will not be sensing the channel while deferring the countdown. Instead it will enter the backoff state using the NAV from the CTS packet to conserve energy. This technique allows sensor nodes to make a random access request based on the channel activity without drastically increasing the energy consumption or end-to-end delay.

7.4.2 Performance Evaluation

With reference to Algorithm 2, the DIFS-VSDH-MAC protocol has been simulated with the simulation parameters given in Table 7.2. The throughput performance is shown in Figure 7.12 as a function of traffic offered load, with $n = 50$ and $M = 4$.

Figure 7.13 shows the maximum throughput performance of the DIFS-VSDH-MAC protocol compared with other DMAC protocols, it can be seen that although it does not perform as well as CMDMAC with an idealised sector antenna, it performs similar to CMDMAC with the realistic antenna patterns, with better energy and delay performance.

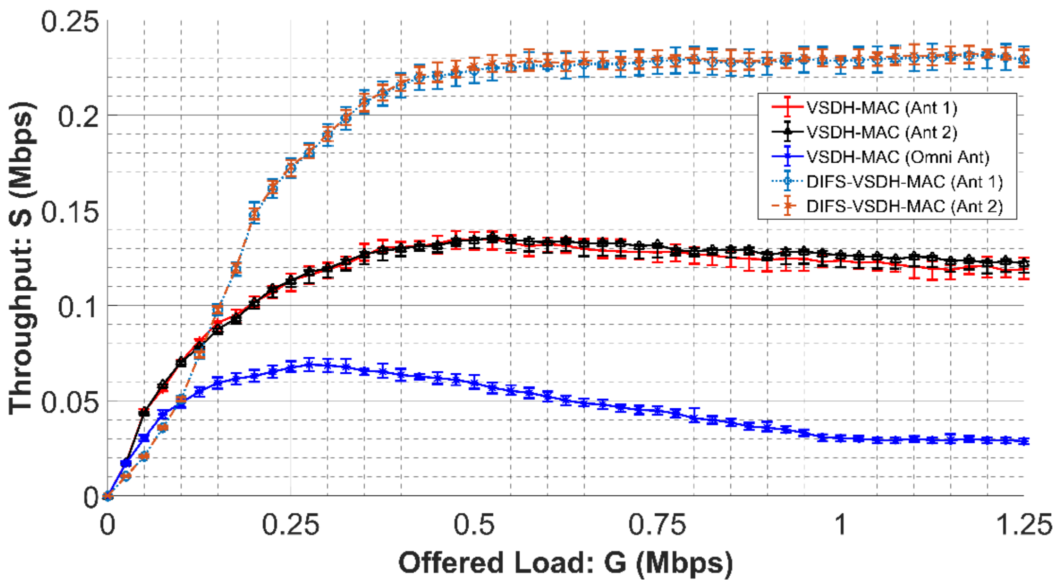

Figure 7.12. The throughput performance of VSDH-MAC and DIFS-VSDH-MAC protocols with different antenna patterns with $M = 4$, compared against the VSDH-MAC with a single omni-directional hub antenna.

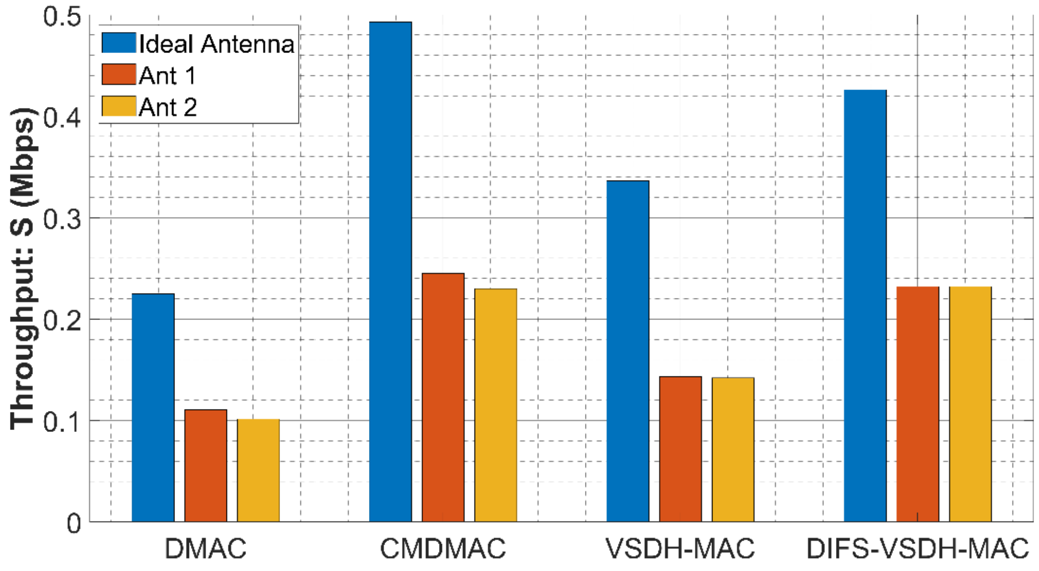

Figure 7.13. Impact of antenna pattern on throughput performance with $M = 4$.

Figure 7.14 presents the additional energy consumption per successful bit for the DIFS-VSDH-MAC protocol. At low traffic offered load, the additional energy consumption is low as the packet transmission frequency is low. Sensor nodes spend most of sleep mode reserving energy. At higher traffic offered load, the extra energy consumption increases as the increasing attempts to access the channel. As more sensor nodes will enter backoff due to the additional carrier sensing, there are fewer packet collisions, reducing the number of retransmissions. Furthermore, when sensor nodes enter the backoff stage, channel sensing is not performed. Hence, the energy consumption for the DIFS-VSDH-MAC is still much lower than the directional CSMA/CA.

The additional sensing provides a much higher overall network throughput performance, but it does not require a significant increase in energy consumption as one might expect. It is important to note that even under a heavy traffic load scenario, the additional energy required is only increased by approximately 7.5%.

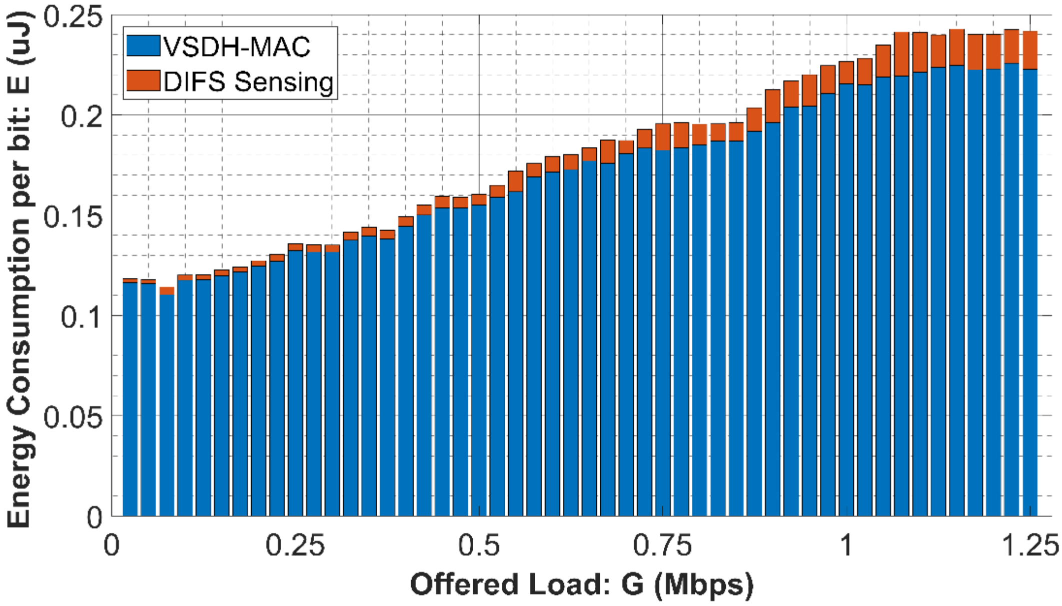

Figure 7.14. The transmission energy per bit for a four antennas DIFS-VSDH-MAC protocol showing the proportion of energy used by DFIS sensing.

The comparative mean end-to-end delay performance is shown in Figure 7.15 as a function of channel offered load. It can be seen that the DIFS-VSDH-MAC protocol provides a very close match to the VSDH-MAC at low traffic loads. However, under heavy traffic load scenarios, the end-to-end delay increases since more sensor nodes are sent to backoff due to the additional carrier sensing.

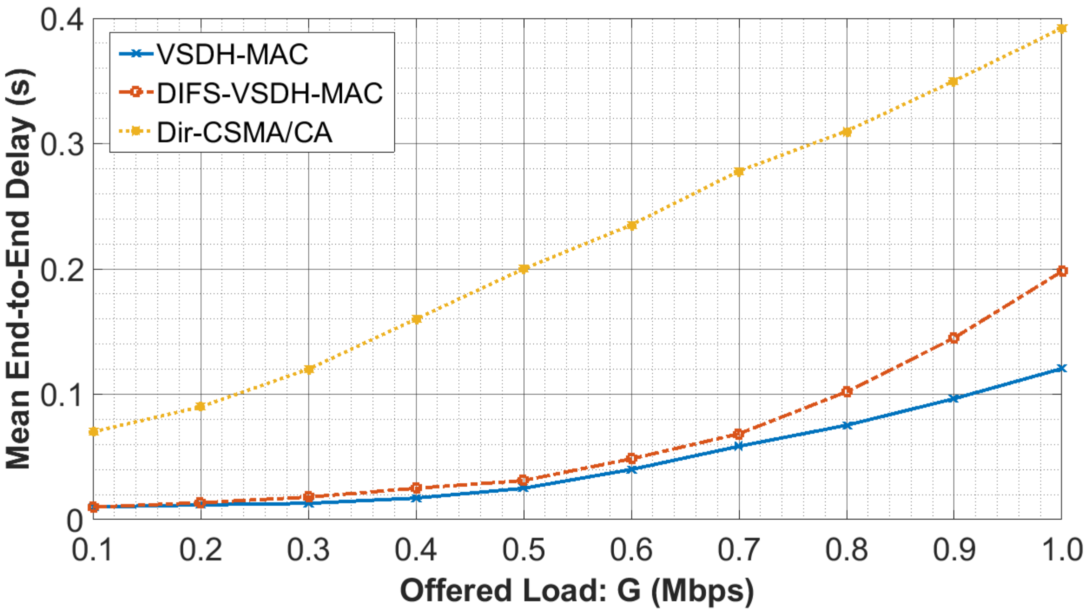

Figure 7.15. Mean end-to-end delay as a function of traffic offered load for DIFS-VSDH-MAC.

7.5 Summary and Discussions

This chapter has introduced a new family of MAC protocols, which incorporate an original approach to the contention-based random access Pure Aloha protocol, suited to supporting directional antennas. The VSDH-MAC protocols combine the virtual channel sensing with good delay performance, effectively supporting a good throughput performance with a large number of sensor nodes with low end-to-end delay for data packet transmissions. Central to this performance is the virtual sensing and antenna reservations. Sensor node uses RTS/CTS handshaking for virtual channel sensing, receiver antenna reservation and power control functions without the need for significant energy consumption. This approach eliminates the delay associated with traditional carrier sensing protocols such as IEEE 802.11 CSMA/CA.

The performance of the protocols has been investigated and evaluated through a combination of simulations with different antennas and hardware platforms. It has been shown that VSDH-MAC is able to offer excellent delay performance, superior to the IEEE 802.11 protocols. The throughput performance of VSDH-MAC has been improved over DH-Aloha proposed in Chapter 5. Performance in terms of energy consumption and fairness are also superior to the IEEE 802.11 CSMA/CA standard due to the proposed power control strategy.

The performance of VSDH-MAC in mobile scenario has also been evaluated. The primary intention of this is to compare the performance of VSDH-MAC-PC in a mobile scenario and in a static scenario. Results show that for mobile scenarios, VSDH-MAC-PC is able to provide the same level of performance as of in static scenarios below a velocity threshold. At velocities above the threshold, it is able to provide the same level of performance as of in static scenarios at a low channel offered load, but the performance decreases as the channel offered load increases.

A variant of VSDH-MAC has been developed, which aims to improve on the throughput performance with the addition of a short channel sensing strategy. The primary feature of this protocol is that the nodes perform channel sensing prior to the RTS packet transmission to reduce RTS packet collisions in order to improve throughput performance.

Significant contributions and advances have been made to the effectiveness of a directional contention-free MAC protocols and it is clear that such protocols are able to provide far better fairness, delay and energy performance compared with those incorporating physical carrier sensing. The performance evaluation presented in this chapter provide strong evidence to support the use of directional antennas and contention-free random access MAC protocol to achieve better throughput, delay, fairness and energy performance.

Chapter 8 Further Work

Contents

8.1 Overview

The issues and techniques associated with effective directional Medium Access Control (DMAC) protocols have been subjected to substantial investigation and development for the wireless sensor networks (WSNs), with numerous studies of DMAC protocols described in the literature in Chapter 3. Previous work has concentrated on improving the network link performance of a WSN by employing directional antennas. However, these protocols are only effective in enhancing throughput performance in ideal scenarios, constrained by the fundamental limits of the directional antenna patterns.

Significant advances in DMAC protocol design for single hub WSNs have been reported in this thesis, primarily through the development of an original approach to contention-free random access protocols, given the understanding of the nature of directional antenna patterns. The Virtual Sensing Directional Hub MAC (VSDH-MAC) and the DIFS sensing VSDH-MAC (DIFS-VSDH-MAC) protocols offer excellent throughput, fairness and lifetime performance and have been subjected to a great deal of analysis and development in an attempt to try to further increase the achievable performance. Since it is believed that any further improvements in the performance for a single channel single hub contention-free WSN are likely to be minimal, suggested areas for further work extend the research into new scenarios, and address some of the wider issues which may have an impact on the DMAC protocol performance.

Section 8.2 presents the ideas for further investigation from the current work, including the applicability of the DMAC protocols in alternative scenarios and further research into how the nature of the directional antenna impacts the performance. Section 8.3 outlines how the work may be extended to a multi-hub or multi-channel architecture. The consideration for a directional to directional WSN is considered and described in Section 8.4.

8.2 Further Investigation of Current Work

All the DMAC protocols presented in this thesis have been evaluated for a 2-dimentional star-based centralised single hub topology. Some useful extension to the work is to investigate the applicability of the proposed protocols to alternative scenarios such as different network architectures and topologies.

8.2.1 3-Dimensional and Non-line of sight Scenarios

Previous research has shown that the implementation of directional antennas can significantly improve the performance of WSNs, especially at providing high SINR. However, the key properties of the protocols and modifications have been tested sufficiently with 2-dimentional simulations on a line-of-sight (LoS) centralised network topology. It would be interesting to have the performance evaluation of the protocols observed on a 3-dimentional scale. In many situations, the 3-dimentional antenna pattern will be affected by the degree of overlap. Therefore, the performance of the proposed protocols may not be the same in a 3-dimentional scenario even with the same number of hub antennas and sensor nodes. Furthermore, since the proposed protocols are not specific to non-line-of-sight (nLoS) scenarios, it would also be interesting to assess the benefits of implementing the protocols in a nLoS or multi-path scenario.

8.2.2 Steerable Antennas at Hub

It was shown in Chapter 5 that the network throughput is heavily dependent on the directional antenna pattern. Comparative performance with varying overlap factor and Signal-to-Interference Ratio (SIR) limit shows that the direction and the SIR limit of the antenna can affect the Signal-to-Interference-Plus-Noise Ratio (SINR) of the packet received due to the receiver antenna gain. Further investigation into the use of steerable directional antennas is required to determine whether steering the antenna main beam towards the transmitting node can effectively increase the SINR with the same antenna pattern.

8.3 Applicability to Alternative Architectures

Instead of a star-based single channel scenario, the VSDH-MAC protocols could be implemented in a multi-hub or multi-channel scenario, where each sensor node can select which hub or channel to transmit to with the RTS/CTS handshaking mechanism with selective backoff proposed in Chapter 7. This approach enables sensor nodes to operate without additional hardware requirement, offering the same energy consumption with increased channel capacity and throughput performance. However, successful implementation is reliant on a mechanism to enable the selection of the hub or channel with multiple sensor nodes competing for the channel access.

8.4 Extension to Directional Sensor Node Scenario

There have been a large number of studies on applying directional antennas at each sensor node, driven by the ability to enhance spatial reuse with the directional-to-directional (d2d) communication. As stated in Chapter 3, these protocols involve additional immense complexity and cost of the sensor nodes. A useful area of further work is to investigate and develop a suitable DMAC protocol, combining with random access techniques in a single channel network to provide enhanced performance with minimal sensor node complexity. This method would have the potential to provide enhanced throughput performance, based on the reduced interference caused by the omni-directional transmission from other sensor nodes.

Chapter 9 Summary and Conclusion

Contents

9.1 Overview

Wireless sensor networks (WSNs) that employ directional antennas are considered as one of the key technologies for utilising channel and spatial resources efficiently and most importantly, accommodating the ever increasing demand for throughput capacity and energy efficiency. The techniques and issues associated with designing an effective directional medium control access (DMAC) protocol for a WSN with directional antenna have been investigated in this thesis. The achievable channel utilisation and other performance metrics such as delay performance and energy efficiency is governed by the underlying DMAC protocol. However, an inherent disadvantage of DMAC is its directional antenna pattern, which is normally ignored by others during the DMAC development process due to its simplicity that was brought with the assumptions. The physical property of the antenna patterns significantly limits the WSN performance in challenging realistic scenarios, where idealised antenna must be guaranteed for most DMAC protocols.

The work presented in this thesis has therefore focused on analysing the impact of directional antenna patterns on various performance metrics and thus, improving the adaptability of the DMAC protocols in realistic scenarios. A general summary and conclusion of the work is provided in this chapter, highlighting the main findings of the research, and identifying the original contributions to the field. Various aspects of WSN and scenarios have been introduced in Chapter 2, provided sufficient background material to support the research that was presented in the subsequent chapters, in which an outline of the characteristic parameters that identifies WSN classification and applications is discussed.

Chapter 3 describes the fundamental channel access techniques and issues associated with MAC for WSNs, including a comprehensive literature review of the most pertinent DMAC protocols. Contention-based random access techniques have been selected for investigation as it is a powerful and widely used approach due to its capability to facilitate the desirable features for DMAC protocols. It eliminates the need for the potentially challenging and complex synchronisation and both energy and cost consuming maintenance, whilst enabling the WSN to operate with significantly enhanced performance. The literature review has shown that a hybrid channel access approach is common among the MAC protocols. However, whilst these DMAC schemes are able to provide significant improvements in throughput performance, they remain constrained and fundamentally limited by the directional antenna pattern. It was concluded from this chapter that the key to achieving realistic improvements to different performance metrics is to propose an alternative approach to directional channel access.

Chapter 4 looks at the modelling techniques and performance evaluation methods. The majority of the results presented in this thesis are obtained through simulation models in Riverbed Modeler, as the Riverbed Modeler places fewer constraints compared to real systems, with greater flexibility in the development of MAC protocols and data collection.

A detailed investigation into the performance of contention-free MAC protocols is presented in Chapter 5, to provide an overview of the fundamental behaviour of random access techniques. A novel analytical and graphical technique is presented to evaluate the performance of DMAC protocol with directional hub. It is shown that random access in the form of Aloha is able to provide instance channel access, but it is limited to poor channel utilisation due to contention. Applying directional antennas to the hub node is simple to implement and the simulation results have shown that it is able to provide good channel utilisation. With an idealised antenna pattern, the throughput performance is superior to the omni-directional hub scenario, with the maximum network throughput of M Erlangs, in which M is the number of hub antennas. Realistic directional antenna patterns can also provide enhanced throughput performance, but this is limited by the antenna overlap factor. It is clear that a novel approach to reduce the overlap factor is required to fully explore the potential of spatial reuse and the capabilities of contention-based DMAC protocols. Multiple strategies are developed in subsequent chapters to achieve realistic improvements for contention-based DMAC protocols.

Chapter 6 extends and further develops the DMAC protocol that was proposed in Chapter 5, aiming to maintain the throughput performance whilst providing enhanced fairness performance and prolong the lifetime. Starting from previous work in Chapter 5, a power control strategy is developed for sensor nodes to dynamically adjust the transmission power. The primary advantage of this strategy is improving the throughput performance marginally by reducing the overlap factor.

A new contention-based DMAC protocol is proposed in Chapter 7 with a virtual carrier sensing approach to reduce packet collision. First, an adaptation of the power control strategy from Chapter 6 was proposed to improve the energy and fairness performance of the VSDH-MAC protocol. Next, a selective backoff strategy was developed to achieve further throughput improvement. The proposed CSMA/CA based VSDH-MAC would utilise the RTS/CTS handshaking as a virtual carrier sensing process to reduce packet collisions. After that, the protocol was extended to include a short period of physical sensing prior to the handshaking to investigate the trade-off between energy consumption and throughput performance. It has shown through simulations that the VSDH-MAC with DIFS sensing offers excellent throughput performance, which is superior to the VSDH-MAC, with the cost of higher energy consumption.

9.2 Original Contributions

The original and novel contributions of the work presented in this thesis can be categorised into two distinct areas of work. The major contributions are summarised below.

9.2.1 MAC Protocols

- An original approach to implementing directional hub random access has been developed (Chapter 5). Unlike the simple directional Slotted Aloha protocol proposed in [95], the DH-Aloha protocol enables spatial reuse whilst avoiding increased delay, sensor node complexity, or introducing time synchronisation while also investigating the antenna pattern overlap effect. This work has been published in The Loughborough Antennas & Propagation Conference (LAPC 2018) [18].

- A strategy has been designed to control the sensor node transmission power to provide a uniform SINR for packets from all sensor nodes (Chapter 6). Power control is a resources management technique used to regulate the transmit power of the sensor nodes. It can be applied in both uplink and downlink to mitigate interference among nodes and utilizing assigned resources. Although a number of power control strategies have been proposed [83, 85] to reduce packets' transmit power, this technique significantly improves the energy efficiency and fairness as well as reducing the antenna overlap factor. This work has been published in the International Conference on Information and Communication Technology Convergence (ICTC 2019) [118].

- A new family of DMAC protocols have been developed which incorporate the novel virtual carrier sensing multiple access technique and directional antennas (Chapter 7). Although there are a number of directional CSMA/CA based protocols [93, 94], the VSDH-MAC protocols are able to provide excellent throughput, delay, fairness and energy performance for a WSN for different scenarios by employing a virtual carrier sensing scheme with a single frequency channel, instead of performing continuous physical carrier sensing, with some operating at multiple frequencies. Furthermore, antenna patterns are carefully considered in the VSDH-MAC protocol by the use of selective backoff and power control schemes. This work has been published in the MDPI Electronics 2020 [120].

- A strategy has been designed to control access to the backoff state for the sensor nodes operating with a single omni-directional antenna on a single frequency channel (Chapter 7). This technique can significantly improve the effectiveness of random channel access and reducing end-to-end delay by reducing the number of unnecessary backoff and physical carrier sense. A dynamic NAV strategy was proposed in [94] to reduce unnecessary backoff caused by the exposed node problem, but this approach requires sensor nodes with multiple directional antennas which can operate at multiple frequencies, causing a significant burden on the energy and manufacturing cost. This work has been published in the MDPI Electronics 2020 [120].

9.2.2 Analytical Models

- A novel technique has been developed to predict and optimise the throughput performance of the directional hub based protocols (Chapter 5). Although the performance of some directional random access protocols have been analysed in previous literature, such as the basic directional Slotted Aloha protocol in [95, 96], the directional CSMA/CA in [90], and the multi-channel random access CMDMAC in [94], it is still worth considering the benefits of applying directional antennas to basic protocols such as the Pure Aloha protocol. Furthermore, this model analyses the effects and impacts of the antenna patterns on throughput performance, which have been ignored by previous literature but proven significant. The combined analytical and graphical methods have enabled the achievable throughput performance of the DMAC protocol to be evaluated without time and cost consuming implementation. This work has been published in The Loughborough Antennas & Propagation Conference (LAPC 2018) [18].

- An analytical model for calculating the sensor node energy consumption and lifetime has been developed (Chapter 7), with the trade-off between energy and performance metrics presented in [71-78].While the energy model of the traditional CSMA/CA is presented in [79, 80], with sensor nodes staying the carrier sensing mode instead of idle/sleep, this analytical model incorporates the dynamic sensor node transmit power and the selective backoff proposed in Chapter 7, providing a much more accurate energy consumption and lifetime estimation for the VSDH-MAC protocol. This work has been published in the MDPI Electronics 2020 [120].

Glossary

ACK	Acknowledgement
AoA	Angle of Arrival
BEB	Binary Exponential Backoff
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CCA	Clear Channel Assessment
CDMA	Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CTS	Clear to Send
CW	Contention Window
DH-Aloha	Directional Hub Aloha
DH-Aloha-PC	Directional Hub Aloha with Power Control
DIFS	Distributed InterFrame Space
DIFS-VSDH-MAC	Distributed InterFrame Space Virtual Sensing Directional Hub Medium Access Control
DMAC	Directional Medium Access Control
FDMA	Frequency Division Multiple Access

FIFO	First In First Out
GPS	Global Positioning System
ISO-OSI	International Standards Organisation – Open System Interconnection
LAN	Local Area Network
LoS	Line of Sight
MAC	Medium Access Control
MIMO	Multiple In Multiple Out
NAV	Network Allocation Vector
nLoS	Non-Line of Sight
QoS	Quality of Service
RTS	Request to Send
SDMA	Space Division Multiple Access
SIFS	Short InterFrame Space
SINR	Signal to Interference and Noise Ratio
SIR	Signal to Interference Ratio
TDMA	Time Division Multiple Access
VSDH-MAC	Virtual Sensing Directional Hub Medium Access Control
WSN	Wireless Sensor Network

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