A Cross Layer Opportunistic Routing Protocol for Wireless Sensor Network: Analysis, Modelling and Quality of Service Support

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Abstract

A wireless sensor network (WSN) provides a platform for embedded sensing and ubiquitous computing. For ad hoc WSNs, multi-hop routing has been adopted in order to save communication power consumption. By acknowledging the lossy characteristics of radio channels on low-power WSNs, the Opportunistic Routing (OR) protocol provides an efficient method for exploiting the spatial and temporal characteristics of these wireless networks by considering multiple forwarding relays for each transmission. The main contribution of this thesis is to provide analysis and modelling for variants of the OR protocol for WSNs.

Firstly, based on the basic concepts that underpin OR, we propose a new variant of OR that can be used in WSNs. It is known that communication in WSN is the most power consuming operation; hence, we propose a variant of OR that specifically reduces the total number of transmissions required during the coordination step used in OR. We investigate the effectiveness of this approach and compare it with OR that adopts existing and common candidate coordination schemes. In addition, we also propose a retransmission scheme based on provisional reliability constraints for local loss recovery that can be used in this new variant of OR.

Secondly, we propose a comprehensive new analytical framework that is based on Markov Chain and Queueing theories that takes into account the key component strategies of OR (prioritization, selection and coordination) as well as the communication components of WSN. The proposed framework can be used to model the end-to-end *reliability* and *delay* performances of WSNs using OR.

Thirdly, taking into account the potential deficiencies of OR due to its static coordination scheme, we introduce a variant of OR that is aware of the *online* quality of its selected forwarding relays that we have named as the Adaptive Coordination Opportunistic Routing (ACOR) protocol. We propose a new local metric to be known as the Opportunistic Quality Score for ACOR to improve the performance of WSNs and, in particular, to support Quality of Service delivery of messages in these networks. In addition, we provide an analytical framework for ACOR that incorporates the adaptive coordination scheme that has been developed.

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Abbreviations

ACOR	Adaptive Coordination Opportunistic Routing
ACK	ACKnowledgement
CCA	Clear Channel Assessment
CRC	Cyclic Redundancy Check
CRS	Candidate Relay Set
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTS	Clear To Send
ETX	Expected Transmission Count
GPS	Global Positioning System
MC	Markov Chain
NTC	Non-Time Critical
OQS	Opportunistic Quality Score
OR	Opportunistic Routing
PRR	Packet Reception Rate
QoS	Quality of Service
RTS	Request To Send
TC	Time Critical
TDMA	Time Division Multiple Access

Chapter 1

Introduction

Due to continuing advances in Micro-Electro-Mechanical Systems (MEMS), sensor networks have a huge potential for large scale deployment. Generally, sensor networks act like a connector to the physical world by detecting and monitoring their physical surroundings at close range. Through wireless channels, data collected at these sensors can be queried via either neighbouring nodes or gateways for further processing and action. A Wireless Sensor Network (WSN) is an example of an ad hoc wireless network and it provides a platform for embedded sensing and ubiquitous computing. Currently, sensor nodes have been deployed for all sorts of environments such as on land, underground and underwater. Types of WSNs that have been observed and investigated range from Terrestrial WSN [1], underwater WSN [2], underground WSN [3], multimedia WSN [4] and mobile WSN [5].

1.1 WSN Applications

WSN is thought to be an enabler of ubiquitous computing and hence this leads to a limitless number of possible applications that could be developed. It was envisioned that with the advancement of sensor nodes in both wireless and sensor technologies, WSN would be able to be deployed in a random manner in any kind of environment. Generally, the characteristics of WSN applications can be classified into 2 categories, viz: monitoring and tracking [6]. Nowadays, requirements such as quality of service, energy efficiency, scalability, robustness and self-configuration are becoming more and more important. Due to the large diversity of possible WSN applications, there is currently no protocol that is available to satisfy all these requirements. In addition, wireless sensor nodes are typically resource constrained in terms of energy and computational capability which further limits them from providing solutions that are able to fulfil all requirements.

The specific requirements for each category are very application-dependent to the extent that different requirements may be needed for an application from the same category. For example, event monitoring WSN applications for buildings can have different requirements from environmental monitoring in terms of reporting frequency, accuracy and latency. Moreover, the type of data that WSN applications need to handle also varies depending on its specific requirements. For example, in monitoring WSN applications, certain data is collected at regular intervals and hence some trending or estimation can be performed at the base station if there is missing data for some short interval of time. Alternatively, for time critical information, the requirement for data to be sent in a timely and reliable manner is often crucial. Therefore it is important for any communication protocol operating in this environment to be able to handle such requirements.

1.2 Background and Motivation

With the energy constraint associated with sensor nodes, it has been reported that communication via a wireless medium is typically the most power consuming operation for a wireless sensor node [7]. Hence, a mechanism or techniques related to communication operations should be simple and efficient as well as being energy aware. Unlike traditional wired networks, a WSN poses different challenges and limitations when being deployed for various solutions or applications.

An important feature of wireless networks is the problem of time varying channels due to wireless channel propagation effects such as multi-path fading. This effect can result in large fluctuations in signal strength, thus creating intermittent link behaviour. In addition, a wireless link is a “soft” concept which means that the properties and quality of a link may vary with transmission power, transmission rate, distance and path loss between two communicating nodes. The wireless medium is also, by its very nature, a broadcast medium. Any transmission can be overheard by all nearby nodes that are within its transmission range and therefore can also potentially create noise known as interference. Nevertheless, the benefit of exploiting the broadcast nature of a wireless medium towards improving the connectivity of WSN with unreliable links has been studied in [8]. For a WSN, energy efficiency has usually been of critical concern in network protocol design since each sensor node typically has limited on-board power.

The characteristics of low-power wireless communication have also encouraged researchers to focus on cross layer concepts [9, 10] in designing any communication protocol specifically for WSNs. Through cross layer design, information exchange between any of the layers is permitted in order to improve wireless network performance in a resource-constrained network and it can potentially overcome the drawbacks of a strictly layered design [11].

A multi-hop routing technique has been adopted in WSNs to overcome the transmission range problem and can also save energy. Traditional routing protocols for multi-hop wireless sensor networks have followed the concept of routing in wired networks by abstracting the wireless links as wired links, and then finding the shortest, least cost, or highest throughput path(s) between a source and destination. Since most routing protocols rely on the consistent and stable behaviour of individual links, the intermittent behaviour of wireless links can result in poor performance such as a low packet delivery ratio and a high control overhead. In addition, this abstraction ignores the unique broadcast nature and special diversity of the wireless medium.

In multi-hop WSNs, an effect known as data funnelling [12, 13] can potentially cause the network to become disjoint at the nodes closer to the sinks. In shortest path routing, these nodes will face a higher rate of energy depletion due to the amount of information that converges at these nodes before data can be delivered to the sink nodes. Hence, an alternative routing mechanism that can also perform load balancing in terms of energy consumption in a distributed manner is highly desirable for WSNs.

As a result of the broadcast nature of wireless networks, every packet transmission in a unicast communication to a specific next-hop node of the sender at the network layer, available neighbouring nodes within communication range of the sender may also be able to overhear the packet at the physical layer. Consequently, there is a possibility that these nodes may have received the packet correctly while the designated next-hop node may have failed to receive the packet. Therefore, based on this observation, a different approach has recently been proposed which adopts a cross-layer concept that integrates the network and MAC layers and is known as opportunistic routing (OR) [14-16]. In OR, for every packet transmission, instead of choosing one specific node as the next relay to forward a packet to, the network layer selects a set of candidate nodes as potential relay nodes to forward the packet and, at the media access control (MAC) layer, one node will be selected dynamically as the actual forwarder based on the instantaneous wireless channel condition as well as node availability at the time of transmission. The main objective of the opportunistic routing protocol is to take advantage of the spatial diversity and broadcast nature of wireless communications to resolve the problem of time-varying performance of the links. Moreover, since the path that every packet chooses in WSNs to reach its final destination is not fixed, the problem of funnelling can also be minimised. Thus, in a densely populated and a lossy low power wireless links of WSNs, the opportunistic routing protocol is potentially a good alternative routing method when compared to traditional routing approaches.

Although there are many variants of OR that have been proposed in the literature, typical components that comprise OR include prioritisation of relay nodes, selection of relay nodes and coordination of relay nodes. In general, prioritisation deals with an arrangement of the level of importance for relay nodes, while the selection process involves an operation to nominate the best available neighbouring nodes to become the next relay node for a particular node and finally, coordination is required to ensure that those selected nodes coordinate among themselves in order to continue forwarding the packet(s) that they have received. In typical monitoring and tracking of WSN applications, besides the physical phenomena that is being monitored and sensed, the location of where the information was sensed is also important. Due to this requirement, information about the location of each sensor node in WSNs is assumed to be available either via using GPS technology or some form of localisation technique. Hence, we can exploit location information in the implementation of the OR protocol for WSNs - especially in the prioritisation and selection operations.

There have been many simulation studies in the literature that highlighted the effectiveness of variants of OR in wireless networks in terms of throughput, latency and energy efficiency [14-20]. Alternatively, by resorting to analytical methods, there have been several studies that have been conducted to analyse the upper bound performance in terms of the number of transmissions, latency and energy utilization in the general OR context [21-24].In these works, the coordination overhead of OR was not taken into account and always assumed to be “perfect” in the model. In addition, analytical frameworks for specific variants of OR have also been proposed. In [25-27], analytical frame works for OR that adopt a Request to Send/Clear to Send (RTS/CTS) mechanism for the selection and coordination operations were introduced to model a lightly loaded wireless sensor network based on the carrier sense multiple access (CSMA) protocol. Moreover, Baccelli et al. [28] proposed a mathematical framework based on point process theory for an Aloha-based MAC layer for OR that can be used to determine the optimum transmission probability for source nodes in order to minimise the average end-to-end delay incurred by packets. Their variant of OR relies on a complex and powerful technique known as signalling bursts with logarithmic coding of the rank for the coordination operation. As a result, the proposed model also ignores coordination overhead since it assumes perfect coordination in OR.

As mentioned earlier, there are many types of WSN applications. Depending on the application type, different WSN applications may have different quality of service (QoS) requirements such as delay, reliability or energy constraints. In general, supporting these QoS requirements can be addressed within the different protocol layers (i.e. the MAC and network layers) and mechanisms. However, due to the limitations of resource constrained nodes in WSNs, QoS support approaches that have been proposed in [29, 30] and based on end-to-end path discovery, resource reservation along the discovered path and path recovery when the topology changes are actually not suitable for sensor networks. Hence, instead of relying on mechanisms that provide hard-QoS guarantees which involve complex and costly operations, soft-QoS offers a better alternative for WSNs. Soft-QoS is a concept where the QoS requirements are guaranteed with some probability, pr $\left(0 \le pr \le 1\right)$ which can also approximate the hard-QoS requirements with a probability approaching one $\left(pr \approx 1\right)$.

Having acknowledged the importance of meeting the QoS requirements in WSN applications, a suitable mechanism should be devised to provide soft-QoS provision. Even though OR has been shown to be effective in improving the overall performance of WSNs by adapting naturally to the inherent random characteristics of wireless ad hoc and sensor networks, QoS provision is not the major concern in its implementation. Since there are three main components for a typical implementation of the OR protocol, viz; prioritisation, selection and coordination; a mechanism to provide soft-QoS can be implemented in any of these three components. By exploiting the fact that a location-based prioritisation scheme can maximise the expected packet progress per transmission [31] together with the energy efficient selection algorithm proposed for location-based opportunistic routing presented in [14], we opted to address the issue of soft-QoS provisioning at the coordination component of OR in WSNs.

1.3 Scope and Assumptions

In this thesis, we consider a randomly deployed stationary wireless sensor network where all nodes are assumed to be identical with a fixed transmission power and no duty cycle mechanism. Moreover, all sensors transmit on a common carrier frequency using an omni-directional antenna operating in half-duplex mode. In addition, each node stores the distance of its neighbouring nodes to the destination node as well as their link qualities. The distance can be determined through a localisation operation proposed in [32, 33] while the link quality can be measured using a mechanism involving probe messages [34, 35].

1.4 Thesis Contributions

This thesis carries out a study of opportunistic routing for WSNs. The main contributions of this thesis are listed as follows:

- Focussing on multi-hop networks, we propose a variant of OR specifically for WSNs with a priority-based slotted acknowledgement coordination procedure that we have referred to as the *Implicit Acknowledgement* scheme and compare its performance with other approaches involving OR. In addition, an insight into the impact of MAC parameters on this kind of OR is also investigated via simulation studies.
- We define and propose a new and comprehensive analytical framework to model the performance analysis for a variant of OR that uses a priority-based slotted acknowledgement coordination scheme specifically for WSNs. The framework is developed based on Markov Chain and standard queueing theories which incorporates a realistic channel model for WSN, CSMA/CA MAC model, a queueing model and the coordination overhead of OR. In addition, the issue of coordination failure is addressed specifically in the proposed model as opposed to previous works.

- We also introduce a metric to be known as the *Opportunistic Quality Score* which is used in the proposed slotted acknowledgement adaptive coordination scheme for OR to improve a packet's end-to-end delay. In this scheme, we utilise the real-time contextual information of a communication by allowing the OR to autonomously adapt to wireless network dynamicity and change its operation. Simulation results show that, by incorporating the proposed metric in the adaptive coordination scheme, the mean end-to-end delay of time-critical data packets can be reduced.
- Finally, we propose an analytical framework for OR using the adaptive coordination scheme. Basically, we extend the framework developed for OR to incorporate the changes in the sequence of coordination and coordination delay.

1.5 Thesis Outline

The remainder of this thesis is organised as follows.

In Chapter 2, we present an overview of a WSN; in particular, the communication components of WSNs. A review of the Opportunistic Routing protocol is presented in Chapter 3.

In Chapter 4, we provide an insight into our variant of OR for WSNs that has been implemented in this research. In particular, we consider the effects of MAC parameters and the coordination coefficient on our proposed variant of the coordination scheme. In addition, we also present a probability-based retransmission scheme that can be used together with the coordination scheme to improve the reliability of OR.

In Chapter 5, we describe in detail a new analytical framework to model the performance of OR in multi-hop WSNs. The comprehensive framework models the performance of OR by taking into consideration a realistic radio channel of WSN, common issues encountered in CSMA MAC such as collision and interference, priority-based slotted acknowledgement coordination overhead and finally the problem of coordination failure due to radio fading, collision, interference and disconnection among relays in the Candidate Relay Set (CRS) as well as the potential cross-over effect. Validation of our newly proposed framework is performed through simulation.

An adaptive coordination scheme for OR that incorporates the proposed quality metric is presented in detail in Chapter 6. This chapter also highlights a performance evaluation that demonstrates the effectiveness of the proposed variant of OR.

In Chapter 7, we extend the framework described in Chapter 5 to include the resulting changes due to our implementation of the adaptive coordination scheme as proposed in our variant of the OR protocol.

We summarize the contributions of the thesis and discuss possible future extensions in Chapter 8.

Chapter 2

An Integrated Overview of WSN Systems

In this chapter, we shall discuss the principal communication components of a WSN consisting of the radio channel, MAC and routing schemes which represent the most important aspects of multi-hop WSN systems. Finally, we shall discuss an important focus of this thesis which is the concept of quality of service in WSNs.

2.1 Radio Channel

There is a common assumption that the network topology of WSNs can be modelled as a unit disk graph (UDG) [36] with fixed and constant maximum communication distances; however, radio links in a WSN exhibit widely varying reliability over time, space and from node to node [37-39]. In addition, in terms of the coverage area per transmission, there is a significant difference between a radio channel that is based on the IEEE 802.11 standard (WiFi) and a radio channel on a low power WSN as shown in Figure 2-1. This is mainly due to differences in transmission power capability and the architecture of the radio chip. There have been many studies to investigate the characteristics of low power wireless sensor networks [40-42]. Issues such as temporal and spatial correlation as well as link asymmetry were observed. These findings give important information which supports the development of new and more appropriate communication protocols for WSNs.

Studies conducted in [40, 41] showed the existence of three distinct reception regions for wireless communication in low power wireless sensor networks that can be identified as: connected, transitional and disconnected regions, as shown in Figure 2-2. These regions depend on the separation distance between two communicating nodes which are directly based on the location of the sensor node during deployment. Recent studies in [38, 42, 43] have shown that many links are within an area known as the "transitional region" and they may actually have the highest energy efficiency.

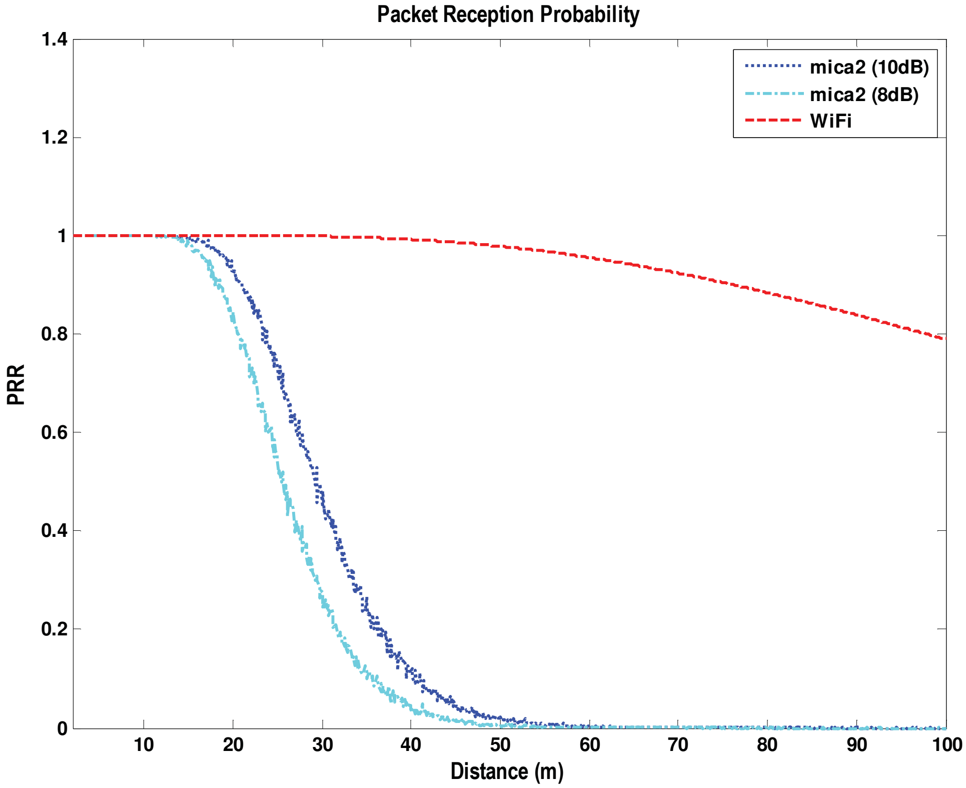

Figure 2-1: The differences in analytical packet success rates (PRRs) between wireless communication involving sensor nodes and WIFI wireless networks. The PRR for Mica2 is determined based on the model developed in [40] while the PRR for typical WiFi is determined based on model proposed in [23].

A theoretical model for the link layer with different modulation and encoding schemes for wireless sensor nodes has been proposed by Zuniga and Bhaskar in [40]. In their model, the wireless channel is characterized as following a log normal shadowing channel model [44]. Based on this model, the successful packet reception rate (PRR) between two wireless sensor nodes can be estimated.

The lognormal path model depends on distance, a path loss exponent, γ (decay rate) and standard deviation, σ (shadowing). The path loss exponent is usually chosen to reflect environmental conditions where the WSN is deployed and is in the range of (2-6). The exact value for one environment can be determined through curve fitting of empirical data. Generally, if we are dealing with an environment that is occupied with many objects and rough surfaces, the path loss exponent will be high. In addition, the author in [40] has also defined the transitional region coefficient, *tr* which is the ratio of the radii of the transitional and connected regions as follows:

$$tr = \frac{d_e - d_s}{d_s} \tag{2.1}$$

where d_e is the end distance and d_s is the start distance of the transitional region from a transmitter respectively. Basically, based on the path loss exponent and standard deviation values, a lower *tr* coefficient implies a larger connected region as compared to the transitional region. In general, for communication between two nodes within the transitional region, the PRR can vary significantly between good and bad in a random fashion as shown in Figure 2-2. Rather than ignoring this characteristic we can exploit this finding to fully maximise the outcome of each communication.

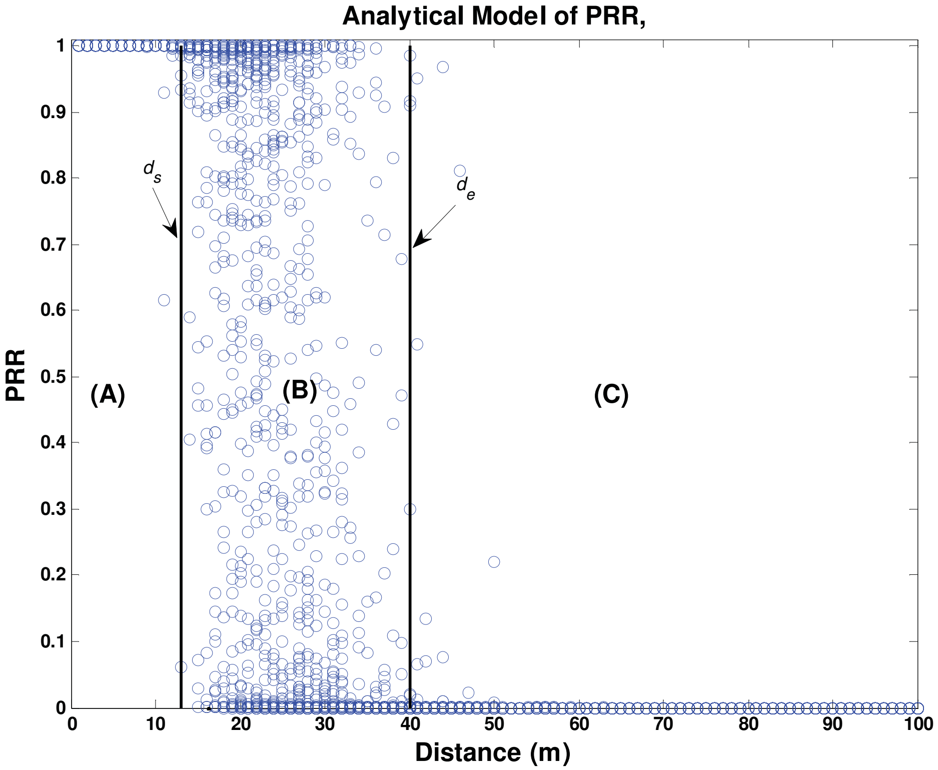

Figure 2-2: The packet reception rate of 100 samples for fixed separation distance (x-axis) between 2 nodes based on Mica2 (Non-coherent FSK, NRZ radio, Transmission power=6 dBm, Path loss exponent=3.5, Shadowing standard deviation=3.8). Regions (A), (B) and (C) represent connected, transitional and disconnected regions respectively. Two vertical lines correspond to starting (d_s) and ending (d_e) of the transitional region.

2.2 Media Access Control (MAC)

The MAC sub-layer determines which sensor node is permitted to access the radio channel at any given time. Several surveys on MAC protocols for WSNs can be found in [45, 46]. Generally, MAC medium access mechanism protocols can be classified into three main categories, viz:

- **Scheduled -** also known as Time Division Multiple Access (TDMA),
- **Contention -** also known as Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) and
- **Hybrid -** combines both TDMA and CSMA/CA in its implementation.

Using a common and shared radio channel, interference is one of the problems that degrade the performance of wireless networks. TDMA attempts to provide channel access solution that is free from interference, which can ensure a high level of successful transmissions. TDMA requires global or local synchronization for each node to maintain a list of its neighbours' schedules. Hence, a predictable and bounded channel delay can be estimated through time slot scheduling that depends on the amount of traffic and the network density. A centralised synchronisation is often required which makes TDMA very hard to adopt in resource constrained environments such as in multi-hop wireless sensor networks. Moreover, common issues in ad-hoc wireless networks such as scalability, mobility, efficiency, and robustness contribute to the difficulty of implementing TDMA-based MACs in large scale sensor networks. Some of the commonly used scheduled-based MACs for WSN are PEDAMACS [47], LMAC [48] and the Self-Organizing Medium Access Control (SMACS) [49].

In contention based schemes, the CSMA protocol introduced by Kleinrock and Tobagi [50] is commonly used. The main advantages of a channel access scheme for wireless sensor networks that are contention based are their simplicity and flexibility. In this random channel access protocol, the channel will be sensed through Clear Channel Assessment (CCA) operation prior to any transmission to be sure that is free from any transmission. If the channel is busy (above the carrier sense threshold), a simple back-off technique is used to schedule the retransmission of the packet. For wireless local area networks (WLANs), a mechanism known as the Distributed Coordination Function (DCF) has been widely used and implemented. This mechanism has formed the basis of the IEEE 802.11 standard. Due to its simplicity, the same approach has also been adopted for many of the contention based MAC protocols in wireless sensor networks.

Furthermore, in random contention based MACs for WSNs, a duty cycling mechanism is also adopted for reducing idle listening. Basically, in this scheme, sensor nodes periodically change their radio component states between waking and sleeping states. When adopting this mechanism, coordination between sender and potential receiver is required for a successful communication. There are two types of CSMA/CA duty cycling MAC protocols: synchronous and asynchronous. Synchronous protocols such as S-MAC [51], T-MAC [52] and WiseMAC [53] are based on negotiating a schedule among neighbouring nodes to specify the wake up and sleeping intervals. Conversely, asynchronous protocols are based on the preamble sampling technique in which the receivers wake up periodically to sample and check the wireless channel for a fixed period of time to determine whether there is any transmission. For the sender, rather than coordinating the neighbours' wake up time interval, it sends a preamble of size equal to the sampling period time to ensure the potential receivers wake up during the preamble. Examples of asynchronous protocols that have been developed in recent years are B-MAC [54] and X-MAC [55] which were developed for sensor nodes using TinyOS [56] which is an application-specific operating system for sensor networks..

In hybrid-based MAC protocols, contention-based and scheduled-access schemes are combined to gain the respective advantages of random access and deterministic access. An example of a well-known hybrid-based MAC is ZMAC [57] and IEEE 802.15.4 [58] which is the standard used in ZigBee. In Figure 2-3 and Figure 2-4, typical steps that occur during channel access in IEEE 802.15.4 and B-MAC respectively are shown.

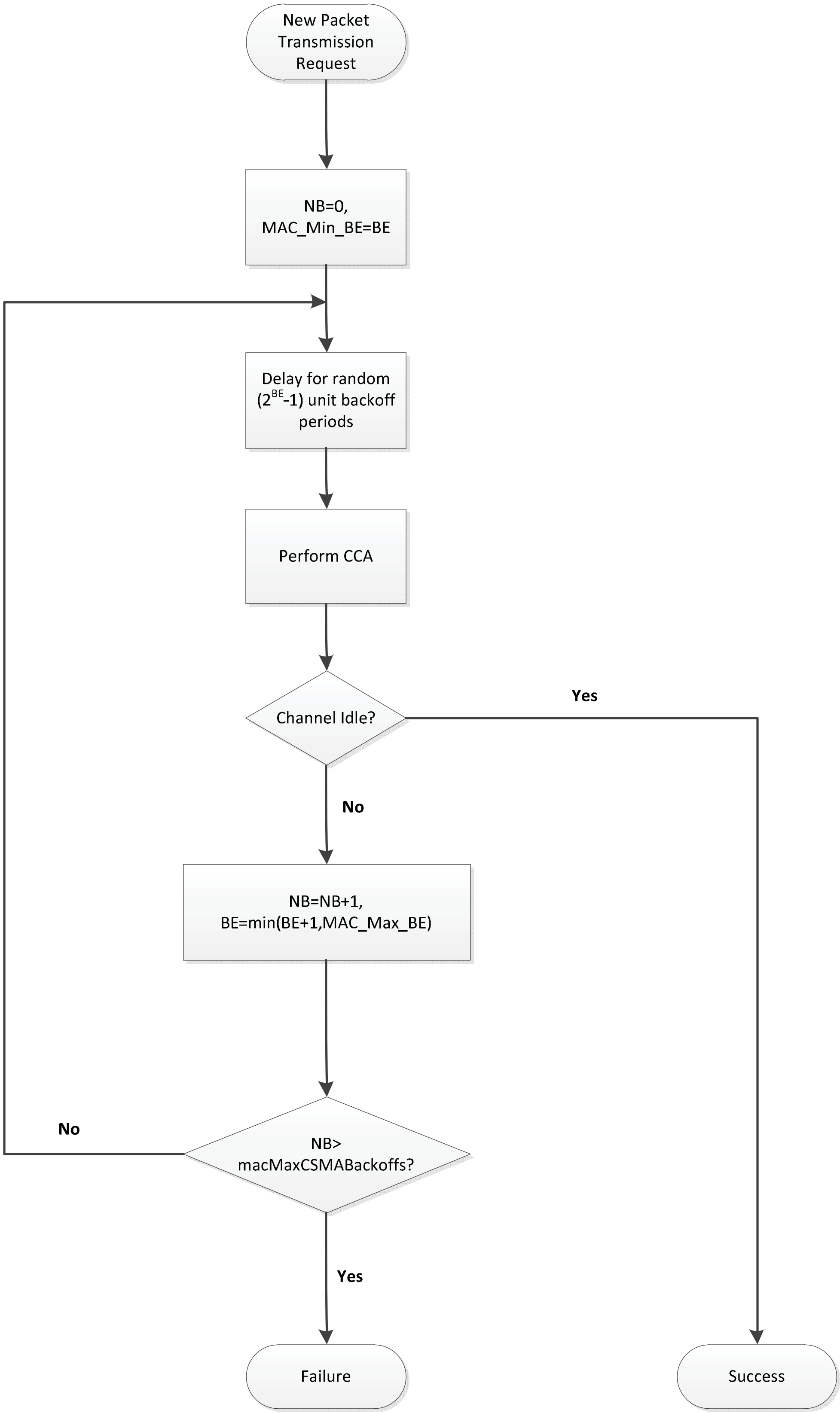

Figure 2-3: Flow chart of non-persistent CSMA/CA implementation of IEEE.802.15.4 MAC. NB=Number of back-offs, BE=Back-off exponent.

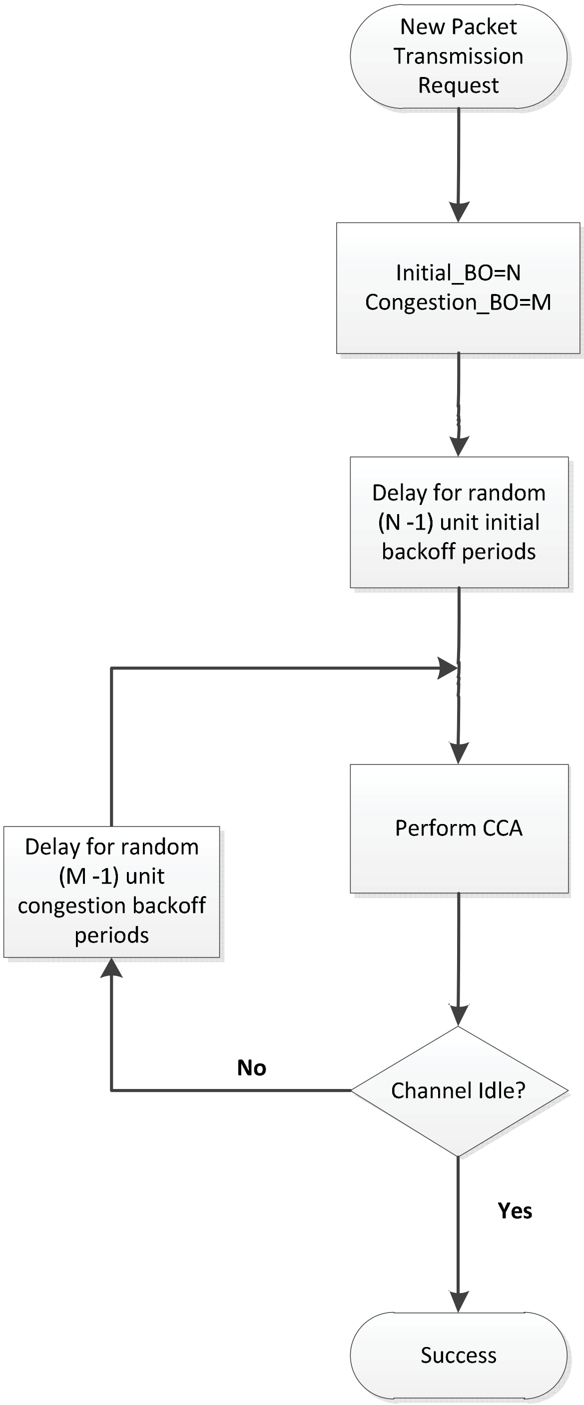

Figure 2-4: Flow chart for a persistent CSMA/CA implementation of B-MAC.

2.3 Routing Protocols and Routing Metrics in WSN

Routing is an important concept in networking for data communication systems. In both general purpose wired networks and wireless networks, a shortest path (or minimum cost) routing paradigm is usually adopted, where a single shortest path between any source-destination pair is computed. In the presence of perfect, static global information, nothing will out-perform a shortest path algorithm. In general, a direct adoption or a variation to the routing protocols used in general-purpose wired networks and mobile ad-hoc networks (MANETs) will not work efficiently and optimally because of WSN characteristics and requirements as highlighted in [1].

Shortest paths are often constructed based on abstract graph-theoretical notions and are oblivious to traffic loads or other constraints. Although shortest path routing is simple, scalable and able to minimise the average energy consumption per packet, it poses several problems in the context of WSNs. Firstly, shortest path routing may suffer from routing instability due to network dynamics (link or node failures) that require network-wide re-computation of shortest paths resulting in more routing overheads and less reliable communications. Secondly, there is a problem of hotspots [59] created due to rapid energy drainage for nodes along the shortest path resulting in a shorter WSN lifetime. Thirdly, bottlenecks at crossing points for different routes can also create problems in WSNs.

In wireless networks, routing protocols face traditional problems associated with the characteristics of a wireless channel such as interference, fading and high error rates. Due to these characteristics, additional routing challenges and design issues that affect the routing process are encountered in WSNs as summarized below.

Node Deployments - Node deployment in WSNs is application-dependent and can be either manual (deterministic) or randomized. In manual deployment, the sensors are manually placed and data is routed through predetermined paths. However, in random node deployment, the sensor nodes are scattered randomly, creating an ad hoc routing infrastructure. If the resultant distribution of nodes is not uniform, optimal clustering becomes necessary to allow connectivity and enable energy-efficient network operation. Inter-sensor communication is normally within short transmission ranges due to energy and bandwidth limitations. Therefore, it is most likely that a route will consist of multiple wireless hops.

Energy Considerations - During the creation of a network infrastructure of WSNs, the process of setting up the routes is greatly influenced by energy considerations. Due to the characteristics of wireless radios in which the transmission power is proportional to the distance, a multi-hop routing approach is a better option since it consumes less energy than direct communication. However, multi-hop routing can potentially introduce significant overheads for topology management and medium access control. Generally, direct routing can be employed if all the nodes are very close to the sink but this cannot be guaranteed if WSNs are deployed randomly within an area of interest. Thus, multi hop routing is unavoidable in WSNs.

Scalability – WSNs potentially consist of a large number of nodes such as for Terrestrial WSNs [1]. In this case, the routing protocol must be able to work effectively. In addition, sensor network routing protocols should be scalable enough to respond to events in the environment. Until an event occurs, most sensors can remain in the sleep state, with data from the few remaining sensors providing coarse quality.

In the last 10 years, research related to routing protocols in WSNs has been actively conducted with many hundreds of papers, surveys and a number of books that focus in this area. In WSNs, to account for and accommodate resource constraints, frequent disruptions and node failures in a challenging environment, routing for WSNs must be carefully designed and optimised - ideally with the ability to locally adapt to changes in data rates and network conditions. In addition, a typical communication pattern in a WSN is between sensor nodes and sink nodes. This type of communication model can be one-to-many or many-to-one depending on the information that is being transmitted. Detailed surveys on routing protocols for wireless sensor networks can be found in [60, 61].

Based on the network structure, the routing protocols for WSNs can be categorised into *flat, hierarchical* and *location-based* routing [60]. Typically, the underlying network structure determines the operations required for the routing protocol in WSNs.

In flat routing protocols, every node plays the same role in both sensing and networking tasks. Based on flat routing and combined with the nature of data sensed in WSNs, a routing concept known as data-directed routing was proposed in Directed-Diffusion [62] and SPIN [63]. In these methods, instead of assigning a global identifier to every node in the network, the routing is based on the application data. Nevertheless, it is still implicitly based on the single shortest-path approach.

The hierarchical-based routing protocols assign different tasks to some nodes depending on their capability through a clustering method. In this approach, nodes that have been assigned as the cluster heads usually are tasked to perform extra operations such as data aggregation or fusion in order to further save on overall energy consumption. The low-energy adaptive clustering hierarchy (LEACH) [64] was one of the first implementations of a hierarchical-based routing protocol. Other common hierarchical-based protocols that were motivated by LEACH are known as the Threshold Sensitive Energy Efficient Sensor Network Protocol (TEEN) [65] and the Adaptive Periodic Threshold Sensitive Energy Efficient Sensor Network Protocol (APTEEN) [66].

By utilizing positional information, location-based protocols relay the data to specific regions of interest rather than sending data to the whole network. The general assumption made for this routing method is that the location information for each sensor node is available either using a small low-power GPS receiver or localization methods based on radio signal strength (RSS) information [32]. We highlight some of the location-based protocols that have been proposed in recent years such as geographic adaptive fidelity (GAF) [67] and geographical energy aware routing (GEAR) [68].

Unlike traditional methods where the network model is based on the assumption that a given pair of nodes is either connected or disconnected, a different scenario has been observed in wireless networks- especially ones involving links in low power wireless communication systems. As highlighted earlier, it has been observed that besides the connected and disconnected regions, many links are within an area known as the *transitional* region [37, 38, 42]. In addition, it is found that the highest energy efficient links typically reside in this transitional region [43]. Hence, routing protocols can be designed by taking the opportunity to exploit this finding.

All the previously mentioned routing protocols can also be categorised as deterministic routing. In deterministic routing, the selected path for every packet is determined *before* data packet transmission. The major argument for not adopting this approach is that the advantage of wireless channel characteristics which is their broadcasting nature is not fully exploited. On the contrary, in non-deterministic or random routing, the chosen path is not fixed for every packet that a sender or relay transmits. The simplest implementation of non-deterministic routing is flooding. The benefit of such approach is that in a resourced-constrained network like a WSN, the problem of hotspots or funnelling can be reduced as well as achieving an increase in reliability. However, the pure flooding approach can lead to problems such as excessive packet duplication, collision and channel contention - also known as the broadcast storm problem [69].

One alternative approach that has been explored and falls under this non-deterministic routing category is called opportunistic routing. This concept follows a different approach from traditional routing techniques with the objective of exploiting the spatial and temporal diversity of wireless networks to cope with the link unreliability. A detail explanation on Opportunistic Routing will be discussed in Chapter 3. In opportunistic routing, the decision to choose the next relay node is made *after* packets have been transmitted. Opportunistic routing extends the idea of geographic routing, by using some nodes that are available for routing at the time the packet needs to be transmitted. It integrates the network layer and the MAC layer where the network layer passes down a set of candidate forwarders and the MAC layer makes a final decision on the node to be used depending on current connectivity. This approach is similar to a *cross layer* approach [9] that takes into account the available information and parameters among different network layers to make more effective routing decisions based on a more informative and current view of the network.

The optimal paths derived from a routing protocol are determined based on specific routing metrics. Initially, routing metrics used in wireless networks were based on metrics designed for wired networks. A commonly used metric in wire-line networks, is the hop count. Even though it is simple to compute, hop count favours paths consisting of fewer, longer hops, which tend to be less reliable than shorter hops due to the characteristics of wireless channels. It was then obvious that direct adoption of these metrics was not suitable for wireless networks, which are dynamic in nature as well as having the properties mentioned above. Alternatively, the Roofnet urban mesh network introduced the expected transmission count (ETX) [70] metric, which utilises link quality information to estimate the number of transmissions required to reliably transmit a packet over a wireless link. Based on the assumption that ETX follows a geometric distribution, it can be determined according to the following expression:

$$ETX = \frac{1}{p_{ij}} \tag{2.2}$$

where p_{ij} is a packet delivery probability between nodes i and j. Baumann et al [71] presented a survey on routing metrics for wireless networks. Intuitively, a good routing metric for a WSN must consider the dynamics of the link conditions to determine the potential routing paths.

2.3.1 Performance Analysis of Routing Protocols of WSN

The performance of routing protocols in a WSN can be evaluated by computer simulation, empirical measurements or mathematical analysis. Typical performance metrics for routing protocols include reliability, latency, energy efficiency and throughput. The option of deciding which testing platform to choose usually depends on the objective of the analysis. There are many simulation tools available. In [72, 73], a study was performed of the different types of discrete-event simulation tools with their associated strengths and weaknesses. Simulation tools allow us to observe the performance of the network of interest easily with many possible configurations such as varying the total number of nodes involved, different network traffic loads or characteristics that they observe as well as the environment where the nodes are deployed. Typically, assumptions based on theory or real observations will be made, to some extent, using these tools. In addition to other assumptions, the investigation of network performance in steady-state conditions normally requires lengthy simulation times involving a reasonable number of repetitions to achieve statistical validity. In terms of empirical experiments on test-beds [73, 74], this approach allows us to measure the performance of a routing protocol based on real data and actual environment scenarios. However, issues such as the difficulty of setting up the experimental test-beds, high costs, lack of scalability test support and difficulty in deploying them within the region of interest contributes to its complexity and disadvantages. In terms of an analytical framework, established theory related to wireless communication [44], queueing [75] and stochastic process models [76] are usually used to analytically predict the performance of the routing protocols. Compared to the previous two approaches, the use of an analytical framework permits the performance of routing protocols to be analysed much more quickly. In addition, the framework also allows optimization analysis to be conducted in order to determine associated parameter values that give optimised performance metrics. Moreover, asymptotic performance analysis can also be done. However, the derivation of an analytical framework may require approximations and simplifications due to the inherently diverse nature and complexity of WSNs. As a result, an inaccurate performance measurement may occur which is not desirable [77]. Thus each of the three commonly used approaches has advantages and disadvantages which must be weighed up whenever undertaking performance analyses for new or modified protocols.

2.4 Quality of Service

Two fundamental issues in practical wireless sensor network (WSN) design are the provision of coverage and connectivity [78]. Coverage is required to make sure that the phenomenon of interest is within the sensing area of at least one active sensor. On the other hand, connectivity involves ensuring that all sensor nodes are connected in the network either by a single-hop or a multi-hop path. Other practical issues such as saving energy and maximising network lifetime are also important, since energy is extremely important in WSNs.

As the technology of WSNs advances, Quality of Service (QoS) will become an important requirement that needs proper attention. This is to ensure that any WSN applications that are deployed will meet their performance objectives with respect to their associated constraints. Due to the unique characteristics of WSNs, QoS support will need to be different from conventional wired and wireless networks. The dynamic nature of multi-hop wireless networks is attributed to time-varying channel conditions, node movements, changing network topology, and variable application demands. Providing hard or guaranteed QoS (e.g., guaranteed bit rate and delay) in such a dynamic environment with random variations is extremely difficult and may even be impossible [10]. On the contrary, in WSNs, the concept of soft-QoS provisioning which is defined as guaranteeing the QoS requirements with a certain probability is more appropriate and attainable [79, 80].

Many potential WSN applications have been envisioned for deployment and they require specific QoS support to meet application requirements. Since WSN applications are usually application-specific, currently it is impossible for us to find a "one-size-fits-all" QoS mechanism for WSNs. Chen and Varshney [81] advocated that QoS support in WSNs can be viewed from two different perspectives, viz: Application-specific QoS and Network QoS.

From the application-specific QoS perspective, the main issues involve the quality of WSN applications. Thus, QoS parameters such as coverage, exposure, measurement errors and the optimal number of active sensors should be considered. From the network QoS perspective, the main concern is how the underlying communication network can deliver the data to meet application requirements through efficient network resource utilisation.

From these observations, to have efficient and effective WSNs applications, good network management is needed because network management operations consume the most energy. However, there is always a trade-off between optimum network management and network QoS. Furthermore, common network QoS parameters that are significant for any WSN applications are also favoured. Parameters related to reliability, timeliness, coverage, robustness and energy efficiency are examples that almost any WSN applications will need. The QoS parameters that can be used to measure the degree of satisfaction of network QoS typically involve throughput, delay, packet loss rate, and energy efficiency. Any communication protocol that can support network QoS requirements and can adapt to network conditions will be useful in the design of WSN applications.

As has been highlighted earlier, one of the main characteristics of nodes in a WSN are the resource constraints; in particular the on-board energy which results in conflicting objectives and thus a trade-off when WSN applications require a certain level of QoS. The problem of energy-efficient communication protocol design for WSNs has been addressed quite extensively in the literature [47, 64]. In terms of the energy efficiency perspective, the most effective solution is to let the sensor node be in the sleep mode as long as possible. A wide variety of solutions for power management that put sensor nodes into a sleep mode have been introduced in [51, 82]. Although the solutions are effective in reducing the overall energy consumption, the major drawbacks of these solutions are: a decrease in reliability and an increase of delay in a multi-hop sensor network [51, 83]. This is due to distributed and random sleep schedules that can lead to non-availability of intermediate nodes that could have assisted in forwarding the packet to the destination during transmission.

2.5 Conclusions

In this chapter, we have discussed the key communication components of a WSN that include the radio channel, MAC and routing. The methods that have been adopted and proposed in a WSN system have been highlighted to give some overview of the current state of WSN research. We further discussed the issue of quality of service in WSNs by highlighting the overall aims and challenges faced when offering a complete solution to guarantee quality of service in WSNs.

Chapter 3

Review of Opportunistic Routing Protocol in Multi-hop Wireless Networks

Wireless network characteristics differ significantly from those pertaining to wired networks. Due to various key differences between these two types of networks, conventional wired networking protocols (especially routing protocols) are considered to be unsuitable in the wireless context. The opportunistic routing protocol was originally proposed to deal with the unreliability and time-varying of wireless link quality. OR is reported to be able to improve the overall performance of wireless networks with fewer transmissions, higher throughput and lower latency [15, 84, 85]. By not restricting to unicast communications that only focus on a single link, OR can utilise the possibility that more distant nodes can successfully receive a packet by "chance" and hence the term "opportunistic". This feature is relevant, especially in environments where there is a high packet loss rate such as in low power wireless sensor networks. With a tight limitation on the amount of energy stored at a sensor node and associated resources, a network protocol that can fully utilise a successful communication attempt can improve the performance of the network in the long run.

Research related to opportunistic routing (OR) has been conducted extensively since the concept was introduced in [15, 26]. Since then, many variants of OR have been proposed which have adopted the concept of opportunistic transmission aiming at the exploitation of the spatial and temporal diversity of wireless networks as highlighted in the surveys [86, 87]. In general, the most common approaches that have been proposed fall into the following two categories:

i) OR with random and unlimited Candidate Relay Set (CRS) [20, 26, 88, 89]
ii) OR with predetermined and limited CRS [14-16, 90]

This chapter examines the operational details and key components of opportunistic routing. In addition, we shall examine relevant literature on OR and its operation.

3.1 General Overview of OR

Figure 3-1 shows a simple linear topology for a WSN consisting of 3 nodes that represent source, relay and destination nodes respectively. The dashed line shows the radio link quality of wireless communication between the two nodes. In traditional wireless communication systems that have adopted the Expected Transmission Count (ETX) as their routing metric, in order for a source node to send packets to its destination node, it would use the static routing path (S → R → D). On the other hand, in opportunistic routing, the existence of a link between S and D is not ignored if the probability of successful transmission is non-zero within its transmission range. Essentially, the decision to select the next hop is based on the communication outcome for each individual transmission. By broadcasting packets from a given node to all nodes that are within its transmission range, OR can leverage on the chances that both nodes R and D can also successfully receive the packet. This technique attempts to exploit the spatial diversity of WSN that is often a typical scenario in dense and randomly deployed networks. In this case, node R needs to be informed that it does not need to forward the packet since it has already been received at the destination node. This routing scheme has been shown to increase the performance of wireless networks in terms of the actual distance travelled by the packets and packet success rate [14, 23].

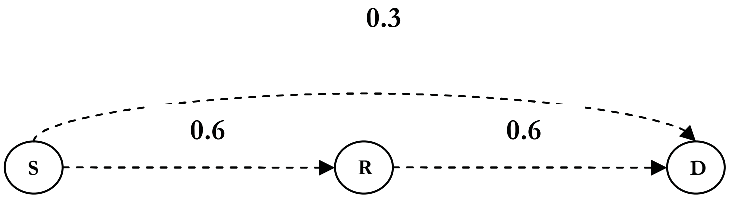

Figure 3-1: Example of simple network topology.

To implement OR, it is necessary to identify three distinct procedures in its operation, viz:

1. Prioritisation of the candidate relay nodes
2. Selection of the candidate relay nodes
3. Coordination of the candidate relay nodes

3.1.1 Prioritisation of the Candidate Relay Nodes

Since in OR, spatial diversity of a WSN is taken into account, this will lead to more than one potential relay node being considered. In this case, these potential relays need to be assigned a priority value. This value is required for the coordination procedure that will be explained in Section 3.1.3. Typically, the priority metric can be determined based on several factors such as the position of the node (i.e. its distance from the transmitting node and destination), link quality, etc. In addition, the priority of relay nodes can also be decided using a specific routing metric which will also be explained later.

Besides being important for coordination, prioritisation is also required to order the potential relay nodes in the selection process. In this case, without a prioritisation order, for node i with N neighbours, the size of the search space or the total number of subsets (T_i) involved for the selection process will be

$$\mathrm{T}_i = \sum_{r=0}^{N} \binom{N}{r} = 2^N \tag{3.1}$$

For example, in Figure 3-2, a two-hop WSN that consists of source (S), relay (R) and destination (D) nodes is shown where node S has 3 neighbours to be considered in the selection process. Hence, in this case, the total search size will be 8. As the number of neighbouring nodes increases, the run time of any selection algorithm would be $\mathrm{O}\left(2^N\right)$ and this becomes impractical in terms of practical implementation. On the other hand, by appropriately prioritising each of the nodes, the search space can be reduced to size N. As highlighted in [14, 18, 90], based on the chosen priority metric or routing metric, with this arrangement, a combination of nodes with n relays in the CRS that gives an optimal value can be determined quickly. Basically, if a CRS with n nodes gives a higher value for the priority or routing metric when compared to a CRS with $n-1$ nodes and a CRS with $n+1$ nodes, the selection process can be terminated. This property ensures that the algorithm to determine a candidate relay set will not involve a polynomial running time cost.

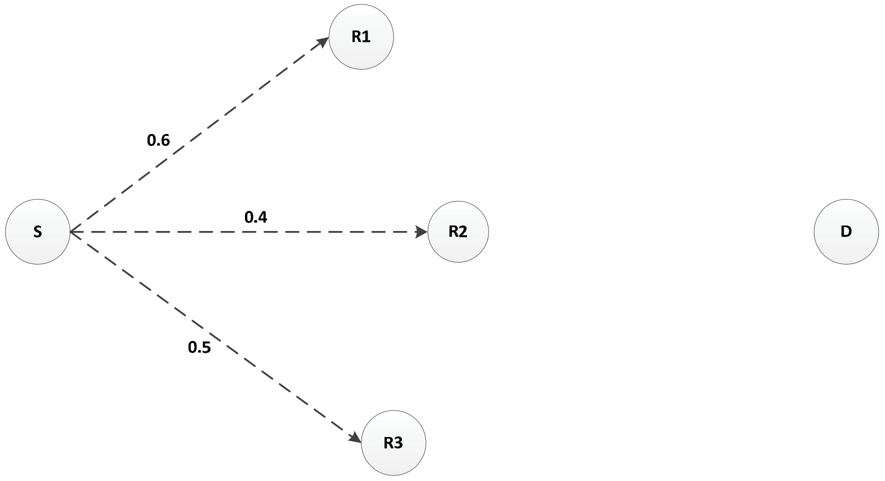

Figure 3-2: Example of two-hop WSN.

3.1.2 Selection of the Candidate Relay Nodes

Ideally, we can simply utilise all the available relays to forward the packet or information towards the destination. However, without limiting the number of candidate relays, the complexity in terms of operation and implementation can be high and impractical. A large number of relays can also offset the benefits gained from the perspective of energy efficiency - especially in a WSN which usually has energy constraints. In addition, increasing the number of relays to be involved in a transmission of the same packet can potentially increase the network traffic thus leading to more interference and collisions. The main objective of the selection procedure is to determine a set of candidate relays which we now refer to as the Candidate Relay Set (CRS) that is optimal with respect to certain criteria (e.g. the packet's distance travelled per transmission, number of transmissions, delay, energy efficiency, etc.). In opportunistic routing, CRS selection algorithms rely on a routing metric to nominate candidate relay nodes with respect to a particular node.

3.1.2.1 Routing Metric

Due to the nature of wireless networks, every transmission is, by default, a broadcast operation. All nodes within transmission range can listen to messages and achieve a different packet reception rate. However, in order to ensure that each transmission is efficient in terms of energy, reliability and accuracy, a proper routing metric to be used in selection algorithms must be devised. Direct adoption of routing metrics for wired networks such as hop count are not preferred due to their failure to reflect wireless link characteristics as noted in the previous chapter. The metric must make sure that only relevant nodes are involved or considered during each transmission. The most commonly used information in calculating such a metric are distance and link quality. The distance information is assumed to be available via GPS or a localisation operation [32, 33] while link quality is determined based on mechanisms such as proposed in [34, 35]. Other information that has also been used in the routing metric will be discussed later.

In addition to the type of information being used, another aspect that has also been taken into consideration when calculating routing metrics is whether the information is local or global. Both types of information have advantages and disadvantages. The advantages of local routing metrics specifically for WSN are that they are computationally simple due to their minimal overhead and that they are not affected by network-wide changes. Any changes to the network that are not local will have no impact on the local routing decision. This characteristic is useful in WSNs due to its particular mode of operation. Moreover, local routing metrics scale well in large networks. However, relying only on local information for calculating a routing metric may not lead to an ideal path. The lack of global knowledge of the network can result in choosing less efficient paths towards the destination. The global knowledge of the nodes and their properties such as remaining power, link quality as well as congestion levels for an indication of the current traffic in the network can be used to determine an optimal path selection depending on objectives that we are wanting to achieve. The overhead and delay cost to obtain global information, are prohibitively high, especially for wireless sensor networks. Furthermore, the dynamicity of network conditions is likely to make the information gathered obsolete and require recalculation. This will impact on the overall gain of using a routing protocol with a global routing metric.

In a static network, a simple routing metric for OR that is based on distance (location) was used in [19, 26, 91, 92]. The variants of opportunistic routing protocols known as Extremely Opportunistic Routing (ExOR) [15] and Simple Opportunistic Adaptive Routing (SOAR) [16] used the Expected Transmission Count (ETX) metric as a basis in their implementation. Based on this metric, a global routing cost metric that gives the estimated number of transmission required to reach the final destination for each node will be determined. Many other variants of OR protocol also incorporate ETX in their global routing metric that include the Expected Any-path transmission (EAX) metric in [85], the Anycast Link Cost (ALC) and the Remaining Path Cost (RPC) metrics in [90]. These metrics estimate the expected number of transmissions required to reach any of the next hop nodes and the expected number of transmissions for delivering the packet in turn from those nodes to the destination. In addition, the Remaining Transmission Count (RTX) and the Actual Transmission Count (ATX) metrics were proposed in [20] to also take into account the expected remaining cost of delivering the packet to its destination from a particular node and all of its CRS nodes.

Lu et al. [93] proposed a routing metric known as the opportunistic expected utility (opEU) metric which combines the benefit, link cost and link quality for an ad-hoc wireless network. A local metric that optimised the throughput known as the expected one-hop throughput (EOT) was introduced in [17]. The EOT metric incorporates link quality, distance and the time that includes the coordination delay cost.

Routing metrics that are aware of energy requirements have also been proposed in recent years. For example, a local energy efficient routing metric was proposed by Zeng in [14] that measures the expected packet advancement per unit of total energy consumption for each packet transmission. On the other hand, in [18] , the expected total cost in terms of transmission power for a particular node and all its relay nodes was proposed.

So far, all of the above routing metrics have been time-invariant due to the assumption of a static network (i.e. the delivery probability does not change over time). Other approaches for calculating the routing metric in OR involved using congestion information gathered at the relay nodes and known as the Expected Delay Cost (EDC) [94]. Basically, EDC takes into account some queueing information to measure the level of congestion in the network. This metric is relevant for a typical general wireless network with multiple sources and destinations.

Table 3-1: Comparison of routing metrics in variants of OR

OR Protocol	Local/Global Cost	Metric
Assistant Opportunistic Routing (AsOR) [19]	Global	Location/distance
Geographic Random Forwarding (GeRaF) [26]	Local	Location/distance
Cooperative Opportunistic Routing (COR) [91]	Local	Location/distance
Region Based Opportunistic Routing (RBOR) [92]	Local	Location/distance
Extremely Opportunistic Routing (ExOR) [15]	Global	Expected Transmission Count (ETX)
Simple Opportunistic Adaptive Routing (SOAR) [16]	Global	ETX
Opportunistic Any Path Forwarding (OAPF) [85]	Global	Expected Any-path Transmission (EAX)
Least Cost Opportunistic Routing (LCOR) [90]	Global	Anycast Link Cost (ALC), Remaining Path Cost (RPC)
Threshold-based Opportunistic Routing (TbOR) [20]	Global	Remaining Transmission Count (RTX), Actual Transmission Count (ATX)
Utility-based Opportunistic Routing (UbOR) [93]	Global	Link quality
Geographic Opportunistic Routing -Throughput (GORT) [17]	Local	Link quality, distance, time
Geographic Collaborative Forwarding (GCF) [14]	Local	Link quality, distance, energy
Energy Efficient Opportunistic Routing (EEOR) [18]	Local	Link quality, energy
Opportunistic Routing Congestion Diversity (ORCD) [94]	Global	Queuing time

3.1.2.2 Candidate Relay Nodes Selection Algorithms

Having an unlimited number of candidate relays can provide an optimal value in terms of the expected number of transmissions required, but it comes with additional complexity and problems. Firstly, with too many candidates, the coordination process can become complicated. In addition, the amount of energy required to perform the required computations at these nodes becomes rather high and ultimately unjustifiable. Many previous works have proposed algorithms to select the best candidate relay from the available neighbouring nodes, namely-: ExOR [15], SOAR [16], Opportunistic Any Path Forwarding (OAPF) [95], Least Cost Opportunistic Routing (LCOR) [90], Minimum Transmission Selection (MTS) [96] and Energy Efficient Opportunistic Routing (EEOR) [18]. The trade-offs between optimal candidate relay sets and selection algorithm complexity were discussed in [97]. ExOR and SOAR are based on ETX and simple in their implementation, while OAPF comes with higher complexity. It was shown that MTS and LCOR are able to give optimal candidate relay sets in terms of the expected number of transmissions from a particular node to a given destination node. However, the main disadvantage of these methods is the increase in complexity in terms of the running times to accomplish the selection process. This is often quite long due to the utilisation of a global routing metric– especially in a dense network and hence is not suitable in dynamic wireless networks that require frequent selection updates. On the other hand, in [14], a candidate relays selection algorithm that relies only on a local routing metric was proposed.

3.1.3 Coordination of the Candidate Relay Nodes

Unlike cooperative diversity routing [98], in opportunistic routing, ideally only one relay node will forward each packet towards the destination for each transmission. With the potential for needing to deal with multiple receptions on nodes in the CRS, coordination between these nodes will be important. Generally, this coordination is conducted at the layer below the network layer (i.e. the MAC layer). The main objective of coordinating these nodes is to prevent duplicate packets from being forwarded to the destination and also to acknowledge successful packet reception for reliability purposes. Moreover, transmission coordination is also important for reducing collision effects in a wireless network which can eliminate all potential gains obtained by using OR.

The broadcast nature of wireless communication typically adds to the complexities associated with interference. However, it also creates some benefits by enabling snooping or overhearing. Taking into account these benefits, most coordination schemes are based on a technique known as priority-based slotted acknowledgement [15, 17, 18]. In this technique (see Figure 3-3), the sender will include priority information about the selected relay nodes in its CRS as an overhead in the data packet so that each node in the CRS will know about the priority of the other nodes. Based on this information, scheduling through a time deferral mechanism which sets the forwarding timer proportional to the priority for each candidate node can be performed and an acknowledgement packet can be sent to the sender with the aim of avoiding collisions and reducing network congestion. To select the next relay node, the sender and all other relay nodes in the list will listen to communication activity among all the potential candidate relay nodes. During the overhearing process, after receiving a data packet, depending on the priority level of the node in the candidate relay set, each candidate node will include the ID of the highest-priority node that has successfully received the packet and sends the ACK packet. Based on this information, each node can decide whether to forward or drop the packet.

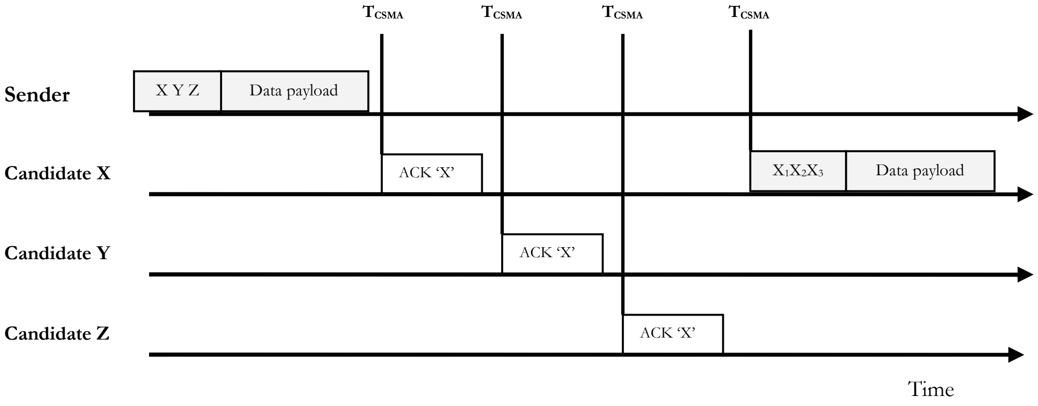

Figure 3-3: Coordination with Slotted Explicit Acknowledgement Mechanism.

The minimum waiting time before the received data packet is forwarded by one of the relays is:

$$T_{min} = 3\left(T_{CSMA} + T_{ACK}\right) \tag{3.2}$$

where T_{CSMA} is the time interval equivalent to an estimated random waiting time to access the wireless channel and T_{ACK} is the time required to transmit an ACK packet.

Another approach is via a three-way handshake procedure proposed in [94, 99]. The procedure consists of three stages in the sequence: 1) transmission, 2) acknowledgement and 3) relaying for each routing decision cycle. Based on these sequences, during the transmission stage, each node transmits a packet. In the next sequence, each node that has successfully received the transmitted packet will send an acknowledgement packet to the sender. Finally, during the relaying stage, the relaying responsibility is passed to one of the nodes that has received the packet or is retained in the sender if retransmission is enabled. The decision about which node will be selected to transmit the packet is done through a control packet known as the forwarding packet (FO). In this three-way handshake operation, explicit ACK packets are required as well as the FO packet for the final decision announcement.

Generally, any variants of OR in a wireless sensor network that limit the number of packet transmissions is preferred. This is mainly due to the presence of resource constraints – especially energy constraints. The main disadvantage of the coordination strategies that are based on control packets such as an ACK packet are that this can incur quite a high penalty in terms of delay which makes it unsuitable for real time or time critical applications. In addition, in a lossy network such as a WSN, ACK packet transmission can also suffer channel errors. Hence, this can basically undermine the acknowledgement procedure.

3.2 OR for WSN

The original objective of OR was to overcome the deficiencies in conventional routing when it is applied in wireless networks that are lossy, unreliable and have varying link qualities. Generally, as mentioned in the previous chapter, the main constraints that we face with regard to WSN are energy constraints and, computational and resource limitations. Hence, it is necessary to take into account these factors when adopting and implementing OR in WSNs.

The logical approach is to incorporate an energy factor into the routing metric for the CRS selection procedure as proposed in [14, 18]. Even though theoretically, we can use all the available relays opportunistically to maximise the overall performance, the overhead in terms of computational complexity and coordination delay will be high. As opposed to LCOR [90] that basically enumerates all of the possible neighbouring relay combinations to determine the best opportunistic route with the least cost, heuristic approaches that emphasise the ordering of the potential relays first, before running the selection algorithm to reduce the search space of finding the optimal relay set were proposed in [14, 18]. The heuristic approach is more suitable in WSNs since its computational overhead will be limited - even though we may just be dealing with a set that could be sub-optimal.

3.3 Performance Modelling of Opportunistic Routing

Previous works, which have evaluated the performance of OR, have focused on using simulations or empirical measurements. However, others have attempted to investigate the performance and the behaviour of opportunistic routing analytically [21-25, 28, 100-102]. The performance metrics such as a packet's average distance progress, the number of transmissions and delay are examples of the many different metrics that have been observed and considered to date.

In [21], the authors proposed a general analytical framework with a specific closed-form expression for the average number of transmissions. With the same objective, [22] proposed a Markov based model to assess the performance of OR. An analysis of the upper bounds on the packet speed that opportunistic routing can gain is studied by the authors in [84]. A model of OR in low traffic wireless sensor networks with an RTS/CTS scheme in CSMA MAC was proposed in [25-27]. Baccelli et al. [28] tried to quantify and optimise the potential performance gains of opportunistic routing strategies compared with traditional routing schemes under the assumption of an Aloha-based MAC layer. In [23, 100], the performance of OR under the effects of a channel fading propagation model on the packet reception rate or link quality was investigated with an optimistic assumption that the coordination cost between network nodes is negligible. Asymptotic analysis of end-to end throughput of OR in a linear topology with type-I HARQ was conducted in [101]. In addition, analysis of a lower bound on the energy-latency trade-off for opportunistic routing with end-to-end reliability constraints in multi hop networks was investigated in [102]. Note that in all previous works, the issue of a coordination procedure was not clearly addressed in their analytical studies. Basically, the authors either ignored or assumed that the coordination procedure was not affected by a wireless channel condition that can lead to communication failures.

3.4 OR with Quality of Service Support

All the previous OR protocols for WSNs [14, 18, 19, 26] did not consider the element of quality of service explicitly in their implementations. Basically, it follows the same concept of *best service effort* as in an IP network once the candidate relay set has been predetermined from the selection process. Recent work in [103] exploited geographic opportunistic routing to provide QoS provisioning with multiple constraints in WSNs. Since typical OR consists of three components viz: prioritization, selection and coordination, a mechanism that looks into the QoS requirements can be applied within any of these three components. For example, we could ensure that the prioritization is set based on the required QoS or selecting a set of relays that can guarantee some level of QoS requirement [103]. In terms of incorporating the QoS requirements in a coordination component, to the best of our knowledge, it has never been implemented.

3.5 Conclusions

In this chapter, we presented, in the detail, the concept of Opportunistic Routing and highlighted previous works related to OR. Acknowledging the benefits of OR to overcome deficiencies observed in the use of traditional routing protocols for wireless communications; additional factors concerned with WSNs especially - energy, computational and resource limitations need to be taken into consideration when implementing the OR protocol for WSNs. Finally, we discussed an approach to incorporate an element of quality of service into the OR protocol.

Chapter 4

Opportunistic Routing Protocol for WSNs: Performance Evaluation

Having acknowledged that there are many variants of the opportunistic routing (OR) protocol that have been proposed in the literature, we focused our scope on proposing a variant of OR that is suitable for WSNs. Typically, OR protocols that incorporate an energy factor in their selection operation is preferable. In addition, any variants of OR that limit the number of packet transmissions is also preferred. This is mainly due to the presence of resource constraints- especially energy constraints. By taking into account these factors, we propose a variant of OR that is suitable for WSNs that deal with time critical data.

In this chapter we introduce a variant of OR for WSNs and present a simulation analysis of this variant of OR. Basically, the simulation studies are conducted to investigate the impact of setting the MAC parameters and OR coordination coefficient delay to the overall performance of a WSN with our proposed variant of OR. Moreover, we also conducted our simulation study to show the benefit of our *Implicit Acknowledgement* scheme in the coordination of OR that we adopted for wireless sensor networks. Finally, performance evaluation of the variant of OR designed to meet a provisional reliability constraint is also conducted and presented in this chapter.

4.1 Variant of Opportunistic Routing Protocol for WSN

In this section, we shall explain the details of a variant of OR that we are proposing. As highlighted in the previous chapter, there have been many variants of OR implemented and studied in recent years. Even though the idea of using OR is to increase the performance of wireless networking and reduce the impact of lossy networks, most of the proposed OR variants require extensive and complex algorithms for relay priority and relay selection. Owing to the characteristics of wireless sensor nodes with resource constraints, these algorithms typically will not be practical for direct adoption in a WSN domain. In the following sections, we shall elaborate on the details of the variant of OR that we have proposed and adopted in our study and provide a justification for our approach. Figure 4-1 shows an example of OR operating in a WSN with one source node and its candidate relays. In this example, the priority level $(Ᵽ)$ of candidate relays are set in an order such as $(Ᵽ_E > Ᵽ_D > Ᵽ_C > Ᵽ_B)$ where node E and B are the highest and lowest priority relays respectively.

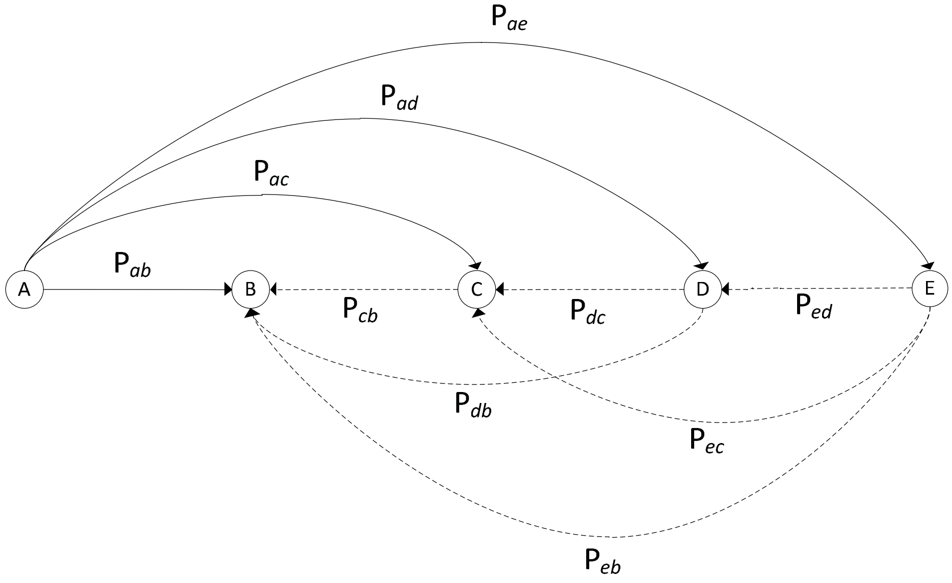

Figure 4-1: Example of OR operation in WSN. The solid lines show the communication between node A and all its priority ordered candidate relays. The labels indicate the link qualities (PRR) between nodes. The dashed lines show communication among the candidate relays during coordination.

4.1.1 Prioritisation of CRS

For the prioritisation component of our OR protocol, the priorities for the neighbours of a particular node are simply based on the distance of the neighbours to a destination. Basically, a higher priority will be assigned to a neighbour that is closer to a destination node. This is because, we want the packet to make maximum progress at each hop and get closer to the desired destination. Such a simple mechanism is preferred, since a WSN needs such simplicity in its operation and for the calculations involved because of limited energy and computational power. In addition, Takagi in [31] reported that relays that meet this criteria can maximise the expected packet's progress per transmission.

4.1.2 Selection of CRS

For selection of relays in the candidate relay set (CRS) we adopted the selection algorithm proposed in [14]. The main reason that this method was chosen is due to the fact that the metric used in the selection procedure takes into account the energy for transmission and reception. Thus, it balances the requirements for selecting the CRS that give an optimum value in terms of the expected packet advancement and energy utilisation. Since this algorithm is also able to limit the number of relays in the candidate relay sets, we do not consider any other candidate filtering metrics such as virtual link strength [16], candidate connectivity [16, 104], pruning [15, 88] and packet duplication probability [105] so that we can further reduce the computation overhead.

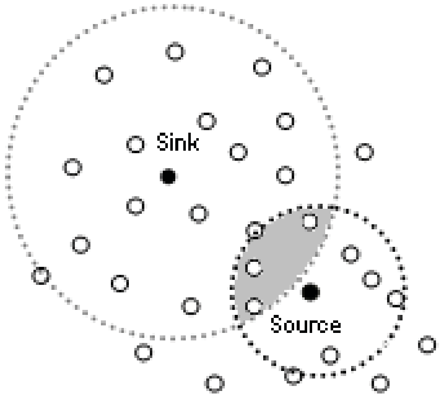

Figure4-2: Overlapping area that represents the forwarding region.

In this method, the algorithm to choose a CRS relies on a metric known as the Expected Packet Advancement (EPA) of a CRS and energy consumption for the CRS. Since we have chosen distance as the priority metric for the available relay node set for a particular node, we can reduce the total number of potential relay nodes to be those nodes that are closer to the destination than the current node. Hence, these nodes are within the overlapping area between the two circles as shown in Figure4-2.

To describe the selection process of a CRS, let n be the number of neighbours for node m that are closer to the destination. In this case, we denote ω_i, $i = \{1, 2, ..., 2^n - 1\}$ as the non-empty subset of m's neighbours with size $r_i = |\omega_i|, r_i \in \{0, 1, 2, ..., n\}$. Note that, the subscript of ω represents the index number of non empty subset of node m 's neighbours. The formula to determine the EPA for a subset ω_i with size r is given by:

$$EPA\left(\omega_i\left(r\right)\right)_m = \sum_{k=1}^{r} d_{k_i} p_{k_i} \prod_{j=0}^{k-1} \overline{p}_{j_i} \tag{4.1}$$

where k is the index of a relay in subset ω_i, p_k is the packet reception rate of the relay node k, $\overline{p}_{j_i} = 1 - p_{j_i}$ and $\overline{p}_{0_i} = 1$. In equation (4.1), $\overline{p}_{j_i}$ is the probability of unsuccessful packet delivery for the higher priority node in the CRS and d is the distance of the relay from the current node, m. In general, this metric calculates the expected packet advancement per transmission that can be achieved using the subset i of the ordered forwarding candidate set $\omega_i\left(r\right)$.

In terms of energy utilisation for each packet transmission, the total energy consumption for each subset ω_i is based on the following expression:

$$E_{\omega_i(r)} = E_{tx} + rE_{rx} \tag{4.2}$$

where r is the number of nodes in the CRS, while E_{tx} and E_{rx} are the energy consumption for the transmission and reception respectively.

Based on equations (4.1) and (4.2), the local metric known as the *Expected Packet Advancement per Energy Consumption* (EPAEC) was proposed as follows:

$$EPAEC\left(\omega_i\left(r\right)\right) = \frac{EPA(\omega_i\left(r\right))}{E_{\omega_i(r)}} \tag{4.3}$$

Therefore, the objective of a selection algorithm is to determine a CRS for each node in WSN with the maximum value of EPAEC (i.e. $\arg\max EPAEC(\omega_i(r))$). Once the candidate relay set has been determined for each node, the ID of the relays in the CRS will be included in the packet as an overhead. Since the selection algorithm that is based on the EPAEC is indirectly able to limit the number of relays in the CRS, the overhead will not produce any signification impact on the total space requirements in the packet and transmission energy consumption. For example, in Mica2, the packet header is 7 bytes (MAC and cyclic redundancy check (CRC) headers) and the default payload size for a packet is 29 bytes. In a lossy network that may require multiple attempts for a successful transmission, the CRS space and energy overhead is balanced out due to there being greater chances of getting successful transmission results per attempt. Thus, whenever the packet is received successfully on relay nodes, the nodes will check whether their IDs match with any of the IDs in the CRS overhead to decide whether to take part to continue forwarding the packet to the next hop. Otherwise the packet will be dropped.

4.1.3 Coordination of CRS

Once the CRS for each node has been determined, the next stage involves the coordination of relays in the CRS. Since multiple relays may be able to receive the packet correctly, the order to forward the packet will be based on their priority. Our approach in coordinating multiple relay nodes is through a procedure that we are proposing and is known as the *Implicit Acknowledgement* procedure. Compared to the previous approaches that depend on the acknowledgement (ACK) packet, the number of steps in each routing decision cycle will only be two, namely: transmission and relaying. An acknowledgement of the reception of packets on candidate relays is through overhearing of the relay's transmission.

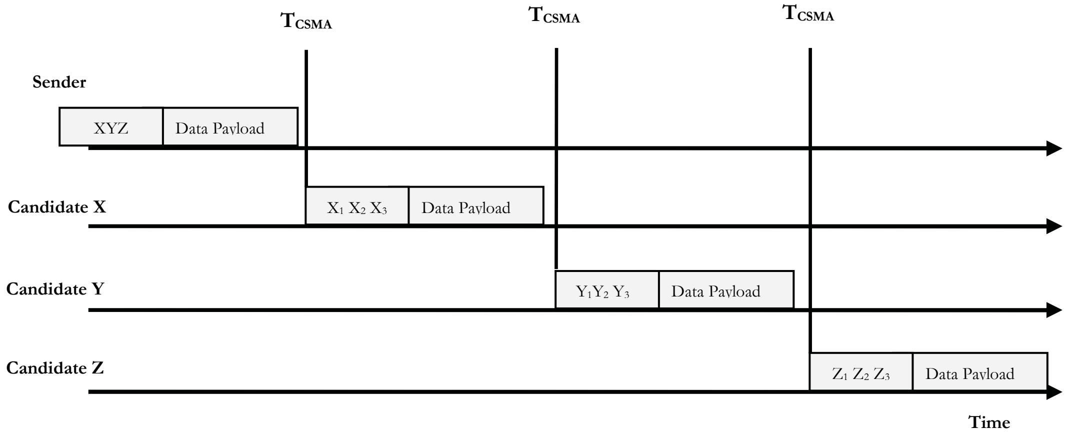

Figure 4-3: Coordination with Slotted Implicit Acknowledgement.

In this approach, based on Figure 4-3, the minimum waiting time that can be achieved before the received packet is transmitted by the highest priority relays in the CRS will only be $T_{min} = T_{CSMA}$. From this observation, the overall latency that a packet will experience in a multi hop network will be lower than if we compare it with the explicit acknowledgement approach. Moreover, through the implicit ACK mechanism, more energy savings can be achieved in the long term due to a reduction in the total number of transmissions that take place in the network.

In addition, by sending the packet straight away (T_{min}), once it is received we can fully maximise the temporal diversity of a wireless network which occurs randomly and instantaneously. In this scheme, using the priority of relay nodes in the CRS, the forwarding time $(T_{forward})$ for each packet that is successfully received at the nodes in the CRS will be scheduled in a distributed manner on each relay node.

$$T_{forward} = T_{cc}\left(\text{Þ} - 1\right) \tag{4.4}$$

Equation (4.4) shows how the forwarding time is determined depending on a fixed coordination coefficient delay (T_{cc}) and priority level $(\text{Þ}, \text{Þ} \in \{1, 2, .., \mathbb{Z}\})$. The priority level for our time and priority-based slotted *Implicit Acknowledgement* coordination scheme is an integer value where a lower value represents a higher priority level. While waiting to forward the packet, the relay will overhear the transmission activity from the higher priority relay nodes and if the packet has been successfully transmitted by the higher priority node, the received packet will be dropped.

4.2 Simulations-based Performance Study

Our performance evaluations of the proposed variant of the OR protocol for WSNs is conducted via matlab-based simulator known as Prowler [106, 107]. Prowler is a probabilistic wireless network simulator, capable of simulating wireless distributed systems, from the application to the physical communication layers. Prowler provides radio and MAC models based on the Berkeley mote platform. It also supports an event-driven structure similar to TinyOS/NesC. With the aim of simulating a realistic implementation of a practical WSN, we set the MAC layer, link quality model, and energy consumption parameters according to Mica2 mote [108] with MPR400 (915

MHz) radio. In the following section, we shall describe in detail the implementation of these models in the simulator.

4.2.1 Link Model

The link model in the simulator is extended to incorporate the model developed for lossy wireless sensor network links in [40]. Basically, the metric used to determine the quality of a wireless link between 2 nodes is based on the packet reception rate (PRR) model. It was derived following on from experimental measures of practical systems with respect to statistics relating to a wireless channel of low power wireless sensor nodes. With the standard non-coherent FSK modulation and Manchester encoding, the PRR ($0 \leq p(d) \leq 1$) of a wireless link is expressible as:

$$p(d) = \left(1 - \frac{1}{2}\exp^{-\frac{SNR(d)}{1.28}}\right)^{8(2f-l)} \tag{4.5}$$

where d is the transmitter-receiver distance, $SNR(d)$ is the signal-to-noise ratio as a function of d, and f is the frame size of 50 bytes which includes the preamble l, the payload and the CRC header. The SNR depends on three components namely, transmission power $\left(P_{t\,dB}\right)$, path loss $\left(PL(d)_{dB}\right)$ and noise $\left(P_{n\,dB}\right)$ on the receiver. The SNR is expressible as:

$$SNR(d)_{dB} = P_{t\ dB} - PL(d)_{dB} - P_{n\ dB} \tag{4.6}$$

The path loss model is modeled according to log-normal shadowing and is determined based on the following equation:

$$PL(d) = PL(d_0) + 10\gamma \log_{10} \log_{10}\left(\frac{d}{d_0}\right) + \overline{X}(0,\sigma) \tag{4.7}$$

where γ is the path loss exponent, d_0 is the reference distance and $\overline{X}(0,\sigma)$ denotes the log-normal shadowing factor with zero mean and σ standard deviation. Essentially, for every packet transmission the PRR value will be generated based on equation (4.5) and if the value is above a prescribed quality link threshold ζ, the communication is assumed to be successful from a wireless channel perspective.

4.2.2 MAC Model

The MAC implemented in Prowler is based on the CSMA/CA scheme which is the default mechanism in B-MAC [54] for Mica2 Motes running TinyOS/NesC with no duty cycle mechanism. Hence, every node does not sleep and is assumed to be always available to hear and receive any packets from its neighbours. One interesting feature of B-MAC is that it provides interfaces for flexible control of B-MAC by the higher layer services. Two important parameters of the CSMA/CA scheme implemented in B-MAC are *Initial_Backoff* and *Congestion_Backoff* parameters which are random uniformly distributed variables in a predefined interval of the contention window (CW). In B-MAC, to initiate a packet transmission, a sensor node will generate a random *Initial_Backoff* time slot interval which is chosen according to a uniform distribution in the range of $\left[CW_{initial\_backoff\_min}, CW_{initial\_backoff\_max}\right]$. Upon expiration of the waiting interval, the channel is sensed. If it is found to be idle, the packet will be transmitted. Otherwise, a *Congestion_Backoff* time slot interval will be randomly generated according to a uniform distribution from a range of $\left[CW_{congestion\_backoff\_min}, CW_{congestion\_backoff\_max}\right]$ before sensing the channel again. In this analysis, we set equal ranges for generating the *Initial_Backoff* and *Congestion_Backoff* time slot intervals. As opposed to the persistent MAC model implemented in Prowler (similar to B-MAC), we modified the MAC model to be non-persistent instead, so that it will continue performing the back-off procedure until the channel is found to be idle - up to a total of m times. This modification is more useful in a dense network with heavy traffic because it can save the sensor node from draining its power as a result of unlimited transmission attempts in a very busy channel.

The simulator also takes into account transmission failure due to a collision caused by hidden terminal nodes which are commonly found in wireless communication networks. Basically, when a collision occurs due to any hidden terminal nodes, the packet that is being received on a receiver as well the packet simultaneously sent by the hidden nodes will get corrupted and this leads to transmission failures.

4.2.3 Energy Model

Since energy is one of the major resource constraints in WSNs, it also useful to be able to determine the overall energy consumption for a communication between a source and a destination. In a WSN, the energy consumption is mainly due to communication activities; in particular for packet transmission, reception and channel sensing. Hence, the total energy consumed for 1 packet transmission is given as:

$$\begin{aligned} E_{total} &= E_{tx} + E_{rx} + E_{cs} \\ &= V(f \cdot I_{tx} T_{tx} + f \cdot n \cdot I_{rx} T_{rx} + m \cdot I_{cs} T_{cs}) \end{aligned} \tag{4.8}$$

Where V is the voltage, f is the packet size, n is the number of receivers, m is the number of times that channel sensing is performed in CSMA/CA MAC; I_{tx}, I_{rx} and I_{cs} are the currents required for transmission, reception and channel sensing, respectively, and T_{tx}, T_{rx} and T_{cs} correspond to the duration of each operation. The energy model for a sensor node is based on a model proposed in [54, 109]. In addition, the model also takes into account the energy consumption when a sensor node is in an idle state. Table 4-1 briefly summarises information concerning Mica2 energy consumption.

Table 4-1: Mica2 energy model

Operation	Duration (ms)	Current(mA)
Transmit (1 byte)	0.200	13.8 (6 dBm)
Receive (1 byte)	0.200	7.0
Channel Sensing	0.175	7.0

4.3 Simulation Settings

In this section, we shall describe two sets of simulation settings that we have used in this simulation study. The first objective of the simulation study is to investigate the impact of changing the MAC parameter, in particular, the *Initial_Backoff* CW and the coordination coefficient delay (T_{cc}) to the overall performance of the OR with the Implicit Acknowledgement priority and time-based coordination scheme. The second objective of conducting this study is to show the effect of adopting the proposed Implicit Acknowledgement scheme in order to improve the performance of OR. Table

4-2 shows the general parameter settings that were used in the simulator for both simulation studies.

We measured the performance of OR in terms of end-to-end delay, packet success rate and energy efficiency. The energy efficiency (bit/joule) is measured as the ratio of the number of packets received at the destination and the total energy communication consumption that includes energy spent on successful transmissions and receptions as well as energy wasted from packet collisions. In our calculations, we focused on the energy consumption of all the active relay nodes that take part in the communication for a given source-destination path. In the following section, we shall discuss the setup and the results of these studies in detail.

Table 4-2: General simulation parameters

Parameter	**Values**
Path loss exponent, γ	3.5
Log-normal shadowing variance, σ	3.8
Link Quality Threshold, ζ	0.1
Receiver Sensitivity	-105 dBm
Transmission Power	6 dBm
Data Packet Length	50 bytes
ACK Packet Length	12 bytes
Voltage	3V
Idle Current	3.2mA
Retransmission Limit	0

4.3.1 OR Sensitivity Analysis

Since OR adopts a cross layer approach in its implementation with the time-based coordination scheme, the MAC parameter setting can influence and affect the performance of OR. We performed simulation analysis to investigate the effect of different parameter settings at the B-MAC layer. The parameter of interest that we are investigating is the contention window (CW) of the *Initial_Backoff* time slot intervals.

Note that in Prowler, 1 slot interval is equal to 25 μs. In addition, another parameter that can potentially influence the performance of the OR protocol is the coordination coefficient delay, T_{cc}. Table 4-3 shows the CW settings for the *Initial_Backoff* parameters that we used in our simulation study. In addition, the corresponding estimated initial back-off interval for each set is also highlighted.

In this study, the simulated network has 25 stationary nodes randomly distributed in a 50 x 50 m^2 square region in which the source and destination nodes are set to be at the points (0,0) and (50,50) respectively. For a low data rate WSNs simulation, the source node is set to be generating Poisson distributed traffic with a mean rate of 1 packet per second. Finally, the results are averaged over 10 runs with 5 different topologies that were randomly generated.

Table 4-3: Contention Window settings

CW Setting $\left[CW_{initial\_backoff\_min}, CW_{initial\_backoff\_max}\right]$	**E[CW]**
[0, 30]	15
[50, 80]	65
[100, 130]	115
[150, 180]	165

In Figure 4-4 we can see the effect of increasing the minimum *Initial_Backoff* time slot intervals of MAC layer upon the end-to-end delay in a multi-hop WSN. Generally, increasing the minimum *Initial_Backoff* time will increase the end-to-end delay since the average per hop delay experienced by the packet will be longer. Furthermore, the longer end-to-end delay is also caused by longer time required to successfully access the channel due to an increase in the network traffic - as shown in Figure 4-5. The reason the network traffic increases is because more duplicate packets are being generated and transmitted by the relay nodes as indicated in Figure 4-6. We can also observe that the effect is similar to OR with a longer coordination coefficient delay, as expected.

In addition, in Figure 4-4, we can also see that the maximum gain in terms of the end-to-end delay ($\approx 25\%$) between 2 different coordination coefficient delays was achieved when the minimum *Initial_Backoff* time slot interval is 0 slot. When the minimum *initial_Backoff* time slot interval increases, the gain reduces due to higher increase in the rate of network traffic for $T_{cc} = 12.5\,ms$ as compared to an increase in the rate of network traffic for $T_{cc} = 25\,ms$. In Figure 4-5, we can observe that there is a significant increase of network traffic when the minimum *Initial_Backoff* time slot intervals were set to 100 and 150 slots respectively. The main reason for this effect was because more duplicate packets were transmitted in the network. In Figure 4-6, the total number of packet duplications is shown. It can be observed that the total number of packet duplications is high for the OR with $T_{cc} = 12.5\,ms$ when the minimum *Initial_Backoff* time slot are set 100 slots ($2.5\,ms$) and 150 slots ($3.75\,ms$). Basically, the high number the packet duplications generated by the relay nodes is due to the total coordination waiting time involved for lower priority nodes in deciding whether the higher priority nodes have failed to successfully receive and forward the packets.

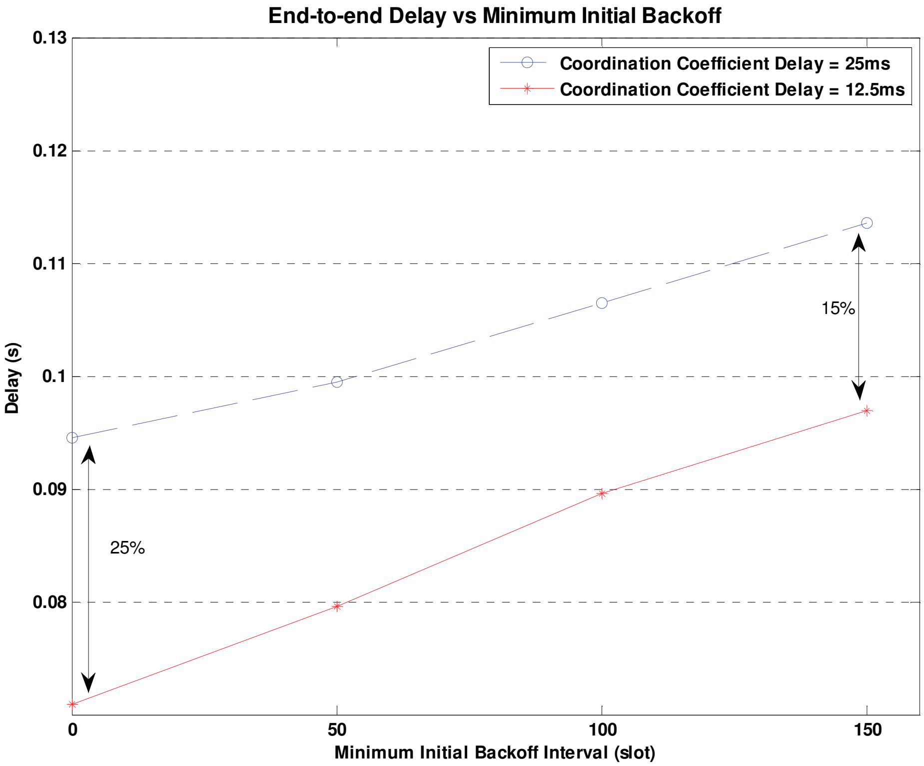

Figure 4-4: The end-to-end delay of OR with different minimum *Initial_Backoff* interval of MAC layer

To ensure that the coordination operation is able to avoid duplication properly, T_{cc} has to be large enough to cover all transmissions from the higher priority nodes. Ideally, it should include the packet transmission time, channel access delay and queueing time. In principle, the general rule to minimise the number of packet duplications is to meet the following condition for the coordination coefficient time (T_{cc}):

$$T_{cc} > T_{BO} + T_{packet} + T_q \tag{4.9}$$

where the T_{BO} is the estimated *Initial_Backoff* time interval, T_{packet} is the packet transmission time which is equal to 10 *ms* and T_q is the expected queuing time. Note that, even if condition (4.9) is satisfied, packet duplication can still occur due to transmission failure during the coordination stage. Thus, the number of packet duplications is still non-zero as shown in Figure 4-6.

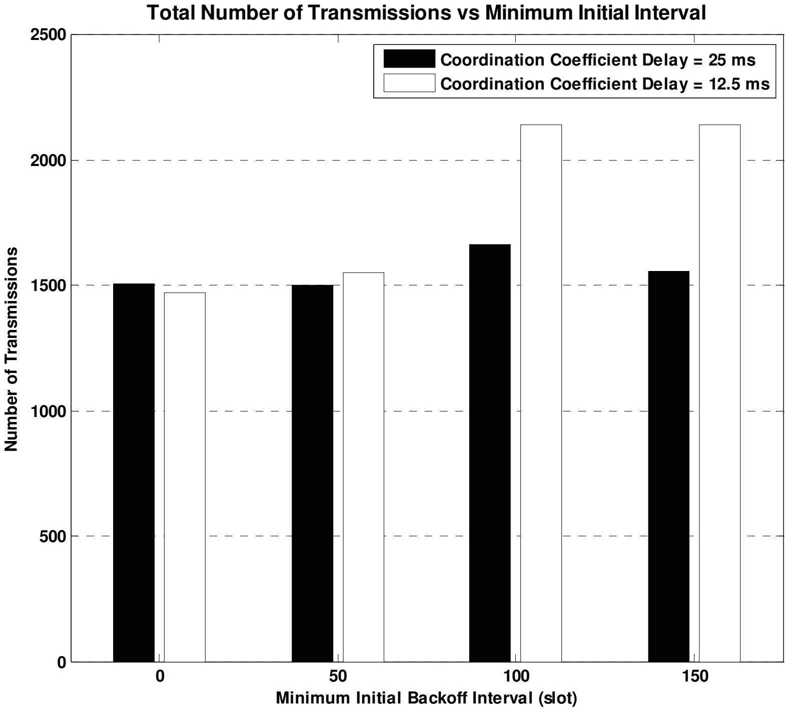

Figure 4-5: Total number of transmissions of OR with different minimum *Initial_Backoff* interval of MAC layer

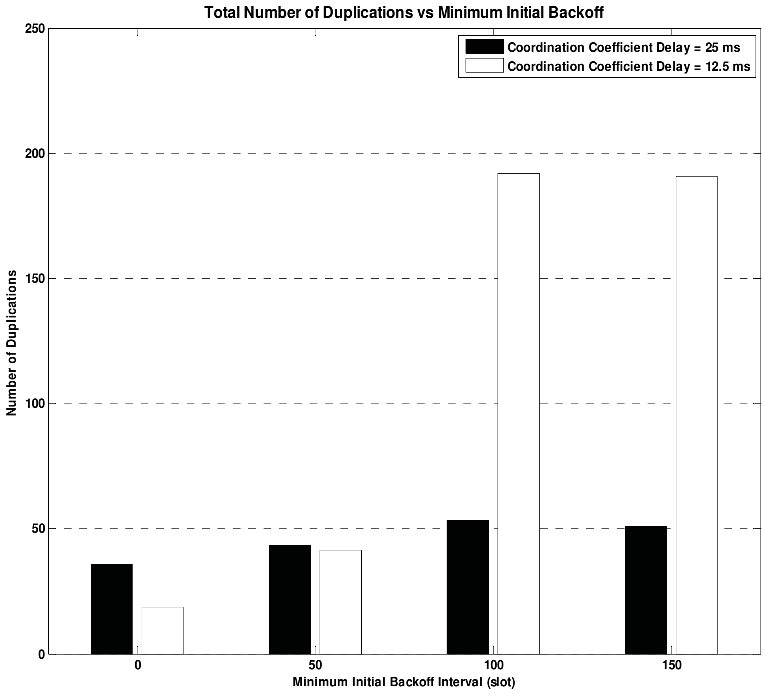

Figure 4-6: Total number of packet duplications of OR with different minimum *Initial_Backoff* interval of MAC layer

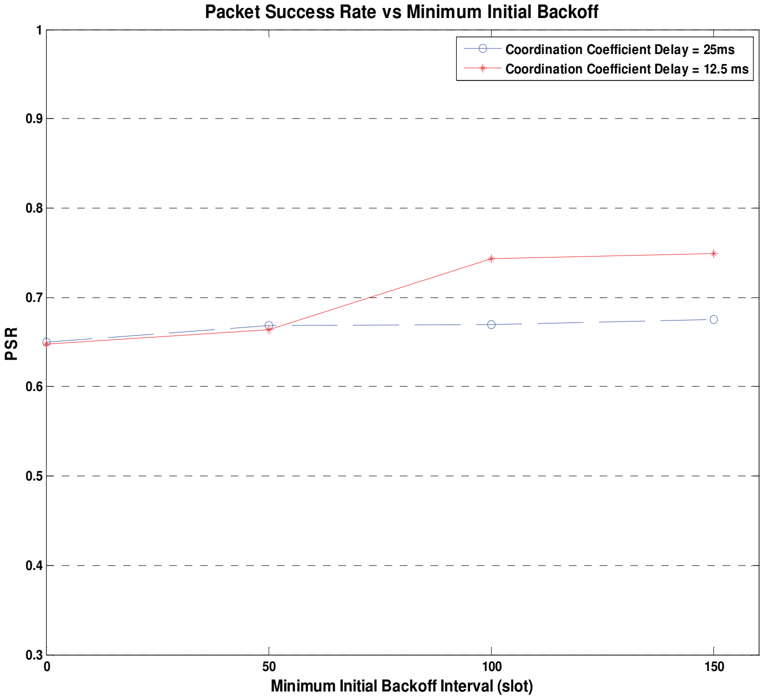

Figure 4-7: The packet success rate OR with different minimum *Initial_Backoff* interval of MAC layer

In terms of packet success rate, the effect of increasing the minimum *Initial_Backoff* time slot interval is illustrated in Figure 4-7. For the OR with $T_{cc} = 25\ ms$, we can see that the minimum *Initial_Backoff* time slot intervals does not have a significant impact on the packet success rate. However, for OR with $T_{cc} = 12.5\ ms$, a significant increase in the packet success rate was observed when the minimum *Initial_Backoff* time slot interval was greater than 50 ($1.25\ ms$). This observation is because of an increase in the number of packet duplications generated by the relay nodes - due to coordination problem mentioned earlier. As a result of more packet duplications, the chance for each packet sent by the source node being successfully forwarded to the destination increases – thus there is a better packet success rate.

Figure 4-8 shows the effect of varying the minimum *Initial_Backoff* time slot interval to the energy efficiency performance for OR in WSNs. It can be seen from the figure that, the efficiency of OR with coordination coefficient delay of 12.5ms decreases consistently as the minimum *Initial_Backoff* time slot interval increases. The reason for this observation is a consequence of the high number of packet duplications that lead to an increase in total communication energy utilisation. Moreover, when the minimum *Initial_Backoff* time slot interval is longer than 100 slots, the coordination procedure for OR will always fail and lead to duplicate packets being generated by the lower priority relay nodes due to the failure of meeting condition(4.9). Hence, in Figure 4-5, Figure 4-6, Figure 4-7 and Figure 4-8 we can see the corresponding measures and metrics converge to nearly constant values.

In terms of energy efficiency of OR with coordination coefficient delay of $T_{cc} = 25\ ms$, overall, the efficiency was not significantly affected by the minimum *Initial_Backoff* time slot intervals as long as the condition in equation (4.9) remains true. In addition, we can also observe that an overall maximum efficiency was achieved when the minimum *Initial_Backoff* is 50 slots. This is because, at this setting, a slightly higher packet success rate was achieved although the total communication energy consumption was almost equal to the total communication energy consumption for OR with $T_{cc} = 12.5\ ms$ and minimum *Initial_Backoff* of a 0 slot interval as shown in Figure 4-9. In general, we can observe that there is a trade-off between the performance of OR in terms of end-to-end delay, packet success rate and energy efficiency with different minimum *Initial_Backoff* time slot intervals for the B-MAC when using different coordination coefficient delays.

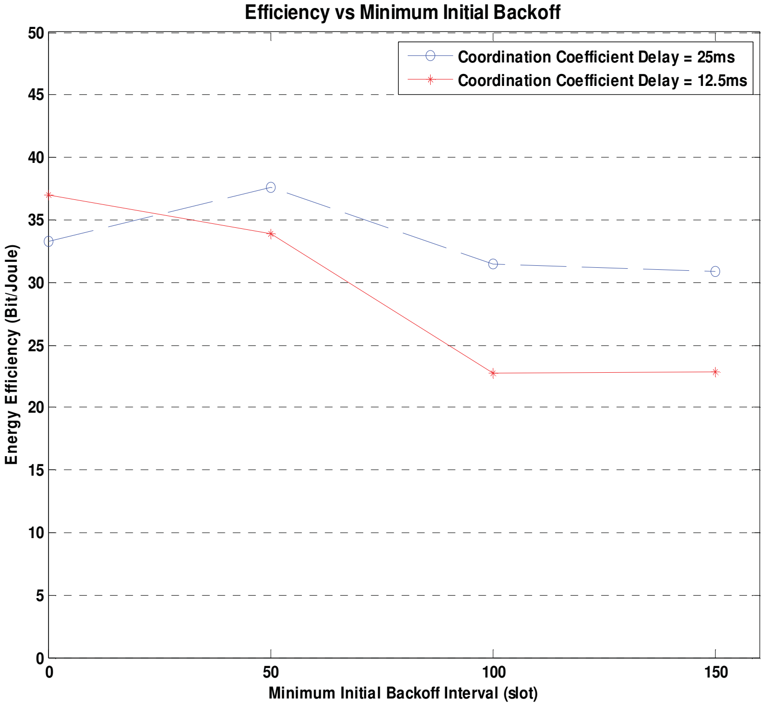

Figure 4-8: Energy Efficiency versus Minimum *Initial_Backoff* interval for the MAC layer

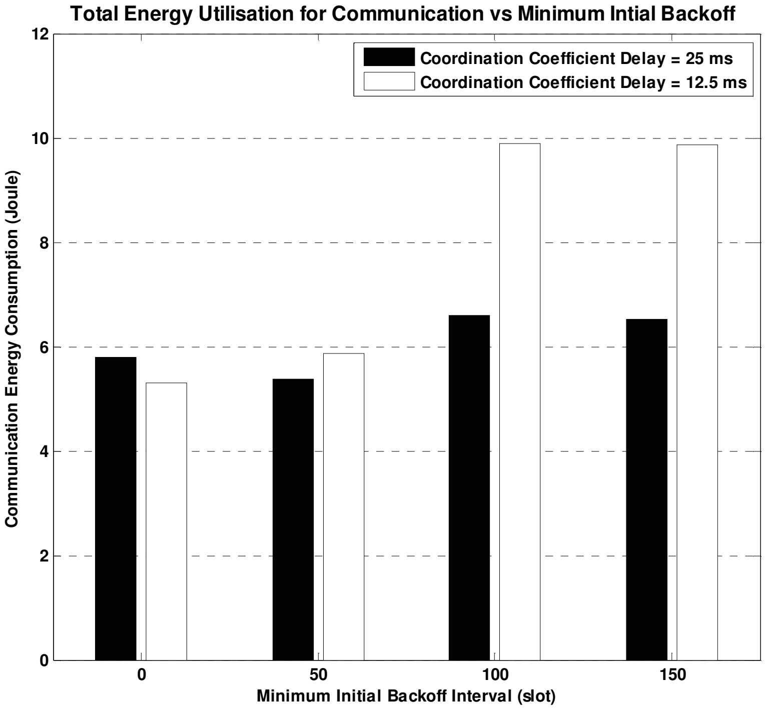

Figure 4-9: Total communication energy utilisation of OR with different minimum *Initial_Backoff* interval

4.3.2 OR with Implicit Acknowledgement Scheme

In this section, we shall present the results of simulation studies that show the effectiveness of adopting the proposed variant of OR with our slotted time based Implicit Acknowledgement coordination scheme. We refer to our variant of OR as described in Section 4.1 by the term Expected One-hop Energy (EOE). In addition, to generalise the effectiveness of the proposed time priority-based Implicit Acknowledgement coordination scheme, we have also adopted a different selection scheme based on a metric known as the Expected One-hop Throughput (EOT) [17]. In this metric, an energy factor is not incorporated into its calculation since its focus is on the throughput metric which measures the expected packet advancement per total coordination time for the CRS. Basically, EOT takes into account the total time required for a packet delivered from a sender to the i^{th} forwarding node in its Candidate Relay Set.

To evaluate the performance of the Implicit Acknowledgement coordination scheme, we setup WSNs with stationary nodes randomly distributed in a 100 x 100 m^2 square region with each node having an identical transmission power of 6dBm. The source and destination nodes are located at the points (0,0) and (100,100) respectively. Figure 4-10 shows an example of two different network densities with 50 and 100 nodes respectively. In this study, we simulate low data rate WSNs in which, the source node generates packets following a Poisson distribution with a mean rate of 1 packet per second. The results are averaged over 5 runs for 10 different topologies that we have randomly generated for each network density.

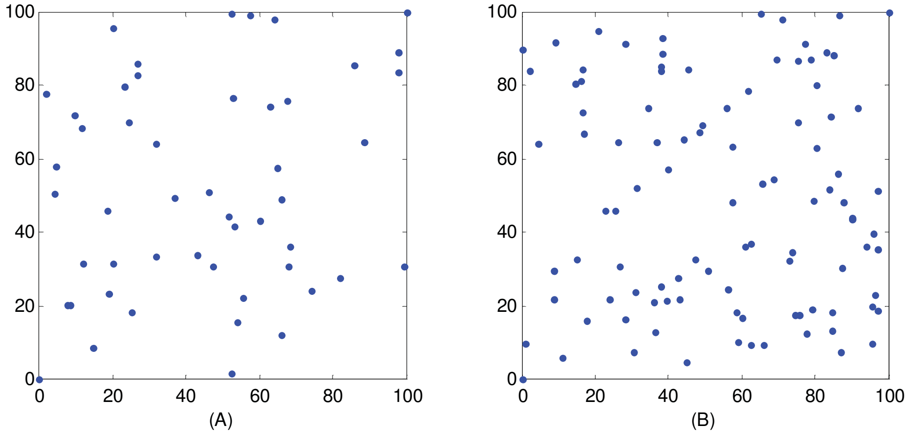

Figure 4-10: Examples of network topologies using a random deployment of 50 nodes (A) and 100 nodes (B)

From Figure 4-11 we can see that the end-to-end delay using the Implicit Acknowledgement (Implicit ACK) approach is significantly lower than the Explicit Acknowledgement (Explicit ACK) method for both types of selection metric. This shows that all the active relays in the network managed to forward packets faster than through the use of the Explicit Acknowledgement (Explicit ACK) mechanism. The same results were achieved for different network densities and this illustrates the advantages possible for the many different scenarios that can exist in a WSN.

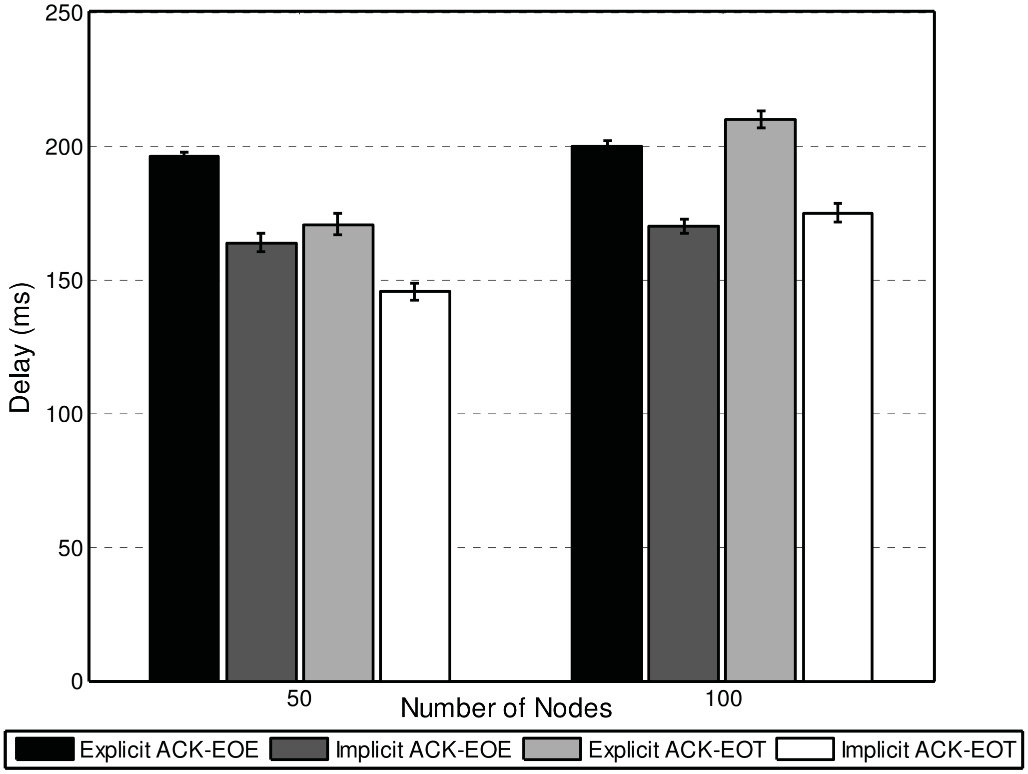

Figure 4-11: End-to-end delay of packets versus network size where $T_{cc} = 15\ ms$ and $T_{BO} = 2.5\ ms$ (Vertical bars show confidence intervals at 95%).

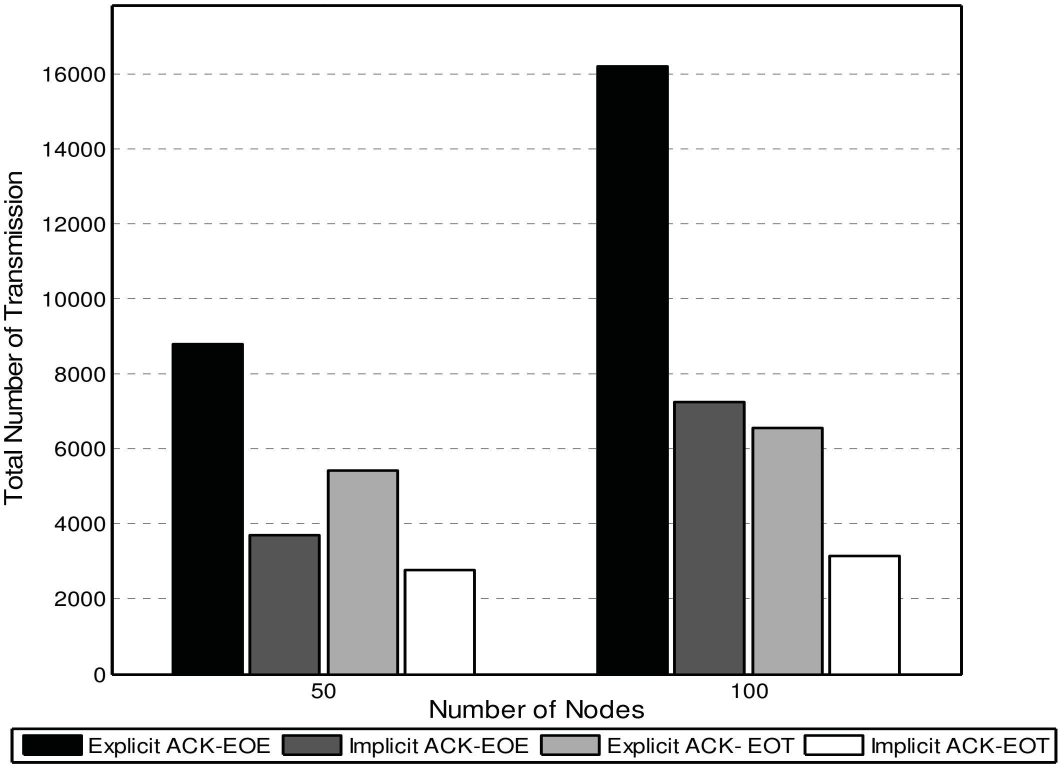

Figure 4-12: Number of transmissions versus network size where $T_{\alpha} = 15\ ms$ **and** $T_{BO} = 2.5\ ms$

In terms of number of transmissions, by relying on the Implicit ACK mechanism, the total number of transmissions performed is significantly reduced as shown in Figure 4-12. As a result, the network traffic is reduced and this leads to fewer collisions as highlighted in Figure 4-13.

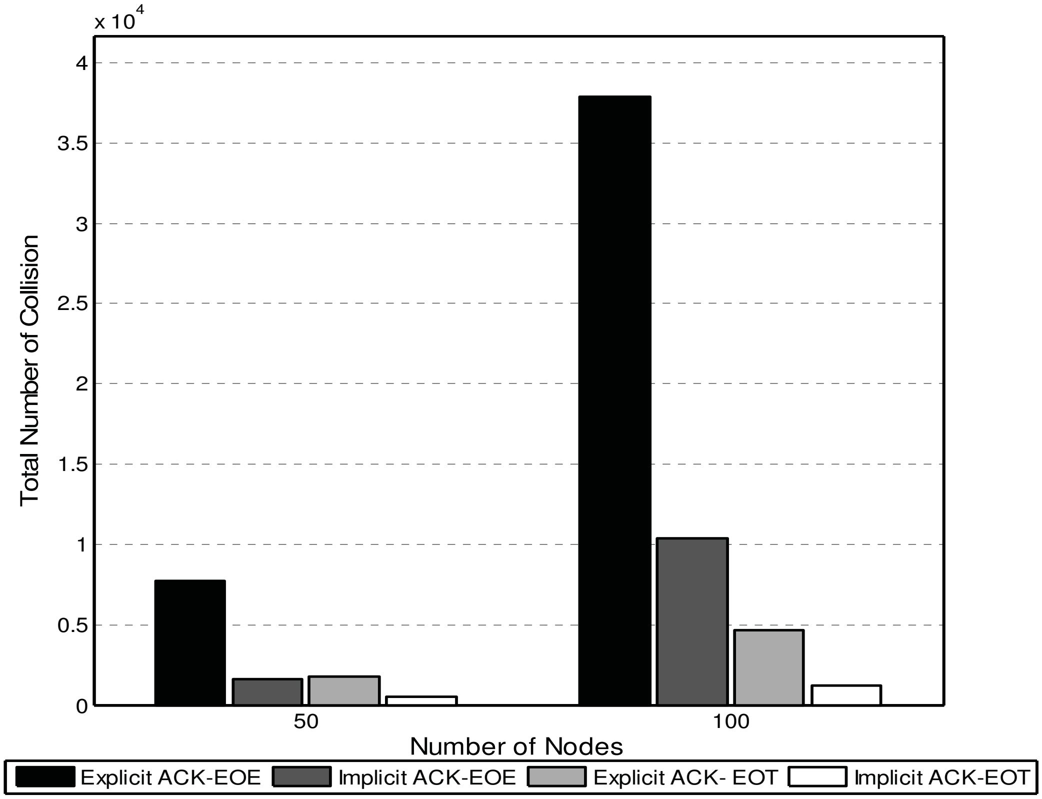

Figure 4-13: Number of collisions versus network size where $T_{cc} = 15\ ms$ **and** $T_{BO} = 2.5\ ms$

At a sensor node, the operation that consumes the most energy relates to communication operations [7] (i.e. transmitting and receiving packets). Hence, by reducing the number of transmissions, the overall energy consumption is also expected to decrease. In Figure 4-14, we can observe that, in general, the energy efficiency of OR with the Implicit ACK mechanism is greater when compared to the Explicit ACK.

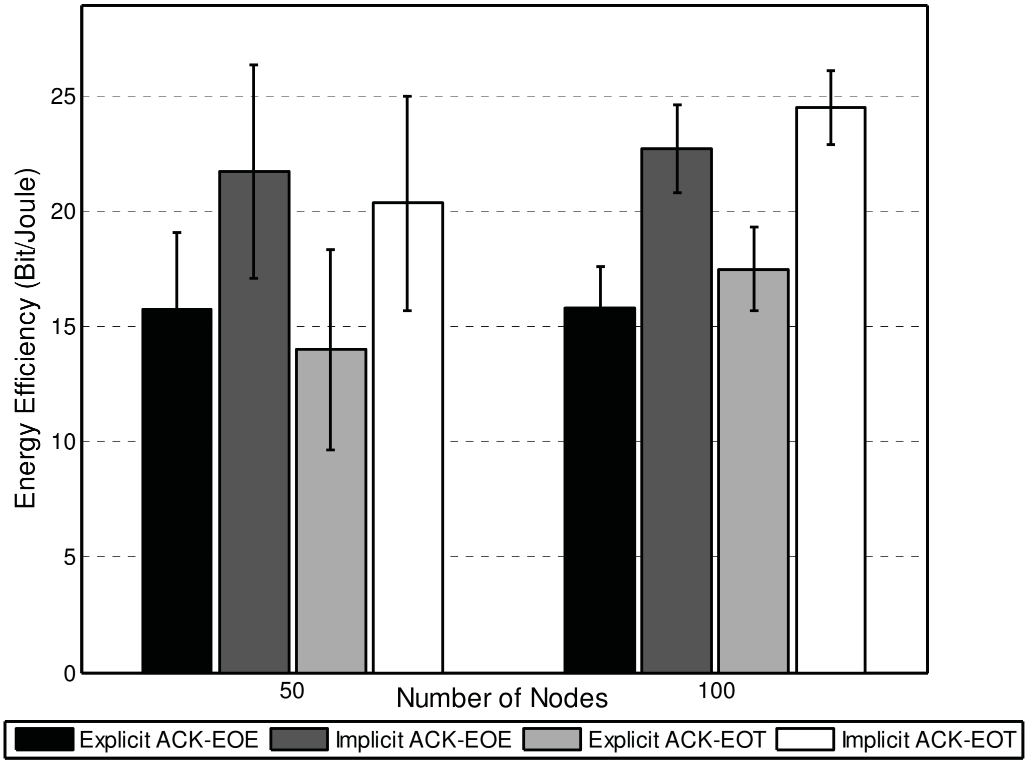

Figure 4-14: Energy efficiency versus network size where $T_{cc} = 15\ ms$ and $T_{BO} = 2.5\ ms$ (Vertical bars show confidence intervals at 95%)

Based on the simulation results that we have presented here, it has been demonstrated that by adopting the proposed implicit ACK mechanism it can indeed improve the overall performance of OR. It is also worth mentioning that this scheme is general enough for all types of OR priority-based coordination - irrespective of the prioritisation and selection metrics being used in the OR scheme as has been shown with the option of the EOT selection metric.

4.4 Soft-QoS: Provisional Reliability

One of the important criteria in any communication is reliability. In wireless sensor networks, hard reliability constraint can be expensive to guarantee. Alternatively, WSN applications can opt to provide provisional end-to-end reliability by setting a threshold for the required reliability, depending on the application requirements. In general, a retransmission mechanism is a common and simple capability that can be implemented to meet such reliability requirements.

Due to the coordination operation in OR; in particular, for the time priority-based Implicit Acknowledgement coordination mechanism, the retransmission procedure needs to be implemented by taking into account the amount of time that has elapsed before making the retransmission decision to ensure its effectiveness. Issues such as collision and duplication can potentially result in overall inefficiency of WSNs with OR as has been shown in the previous sections.

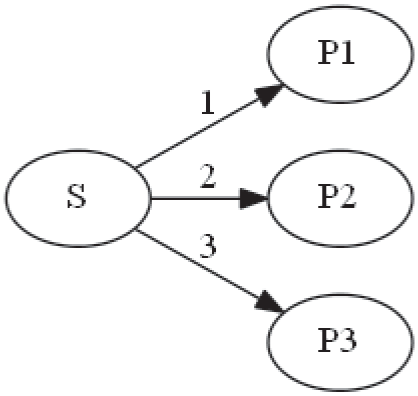

Figure 4-15: Example of communication between node S and its candidate relays (P1, P2 and P3). The labels indicate the priority order for each candidate relay with respect to node S.

Figure 4-15 shows an example of a simple network consisting of one sender (S) and its selected candidate relays (P1, P2 and P3). By adopting a mechanism similar to the well-known automatic repeat request (ARQ) mechanism [110] to handle transmission errors in order to set the timeout time for a retransmission, a sender needs to estimate the expected service time experienced at each of the candidate relays. Based on Figure 4-15, the service time for each candidate can be estimated as follows:

$$\begin{aligned} \mu_{P1} &= t_{pkt} + t_{cb} \\ \mu_{P2} &= t_{pkt} + t_{cb} + t_{cc} \\ \mu_{P3} &= t_{pkt} + t_{cb} + 2t_{cc} \end{aligned} \tag{4.10}$$

where t_{pkt} , t_{cb} and t_{cc} represents the packet transmission time, channel access delay and the OR coordination coefficient delay respectively.

Therefore, the total timeout for a retransmission attempt for each packet from a node with CRS of size n can be approximated as follows:

$$T_{timeout} = n\left(t_{pkt} + t_{cb}\right) + \sum_{i=1}^{n}\left(i-1\right)t_{cc} \tag{4.11}$$

One of the challenges when adopting the Implicit Acknowledgement mechanism is for a sender to determine whether a packet was successfully received at one of its relays since transmission errors may have occurred. In this situation, unnecessary transmissions may take place. Our proposed approach to solve this issue is achieved by calculating the probability of successful coordination among the candidate relays which we refer to as p_{coor} .

When the timeout timer expires, if a sender does not overhear any transmission from its candidate relays, rather than simply retransmitting the packet, the decision to retransmit is based on the probability p_{coor} . By calculating the probability that the lowest priority nodes drop the packet (since it has heard that the higher priority relay has successfully transmitted the packet) a sender can probabilistically decide whether to start retransmitting the packet. In general, the link quality is inversely proportional to the distance. Hence, for a prioritisation procedure that is based on location/distance which is being adopted in our variant of OR, the highest priority is the furthest relay which also has a lower link quality. Conversely, the lowest priority relay has a better link quality and thus a higher probability of successfully receiving the packet from a sender.

During the coordination stage, the lower priority nodes will only forward the packet if any of the higher priority nodes fail to receive and transmit the packet. Based on this procedure, a sender can rely on transmission activity on the lower priority nodes to determine whether to retransmit or not. For any relay that has a low link quality, the chances of the sender being successfully informed using Implicit Acknowledgement could be low. Thus, it is relying on activity on the lower priority relays to infer that the packet has been successfully forwarded to one of the next relays in the sequence.

Basically, lower priority relays have a better link quality and greater chances of receiving the packet correctly. On the other hand, inter-candidate communication is assumed to be better as compared to that which is between the sender and the relays in the CRS, since the distances between these relays are smaller. With this fact, except when the relays in the CRS are disjointed from each other, the probability of a relay being informed about the success of a higher priority node receiving and forwarding the packet will be higher. Hence, even if the sender did not get any implicit acknowledgement packet it certainly cannot assume that the transmission has failed because no packet has been transmitted from the lower priority nodes; that can also mean that they have dropped the packet from continuing because they managed to listen in to the implicit acknowledgement packet from a higher priority node. Our approach follows a similar approach to that used in probabilistic routing [111]. Through this approach, unnecessary retransmission can be avoided and thus lead to higher energy efficiency as a result of fewer transmissions. The probability of retransmitting the packet is based on the following expression:

$$p_{coor} = \exp(-k * prr_{lowest\_priority\_relay}) \tag{4.12}$$

where $k \in [0, \mathbb{R}^{+}]$ is a constant parameter that models the negative exponential decay constant of the retransmission procedure. When k is equal to 0, this method follows normal retransmission exactly - which means that if a packet is not implicitly acknowledged, the packet will be retransmitted up to maximum number of allowable attempts. In this probabilistic approach, whenever a packet is not implicitly acknowledged, the decision to retransmit will be based on equation (4.12). The k value can be tuned, depending on the level of reliability that is required for the WSN application.

We evaluate the performance of OR with a retransmission capability using our simulation tools. The simulation setup and parameters are the same as described in Section 4.3 and Section 4.3.2. The performance metrics that we observe in this analysis are packet success rate or the reliability and energy efficiency. In Figure 4-16, the impact of increasing the retransmission limit to the packet success rate with a different k value for the two network sizes. The small difference in packet success rate achieved by the probabilistic retransmission approach is due to the probability determined in equation (4.12). Nevertheless, both approaches are able to provide reliability that is greater than 90% with retransmission limits of 1 and 3 for network sizes of 100 and 50 nodes respectively. Hence, depending on reliability requirements and network size, we can set the retransmission limit accordingly.

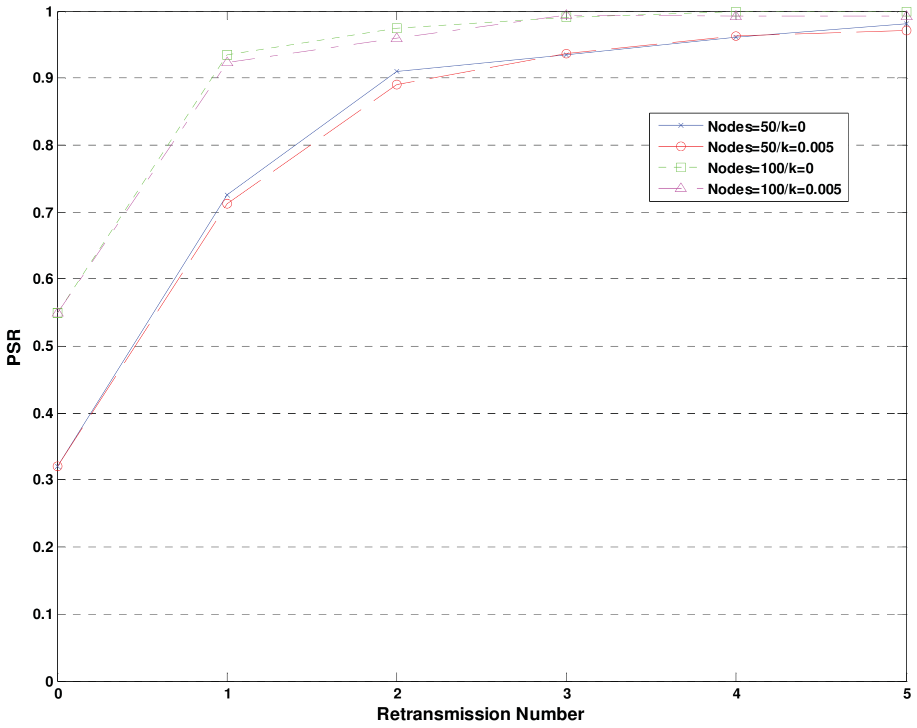

Figure 4-16: The PSR versus the retransmission number for different set of nodes and k factor. $k = 0$ refers to non-probabilistic retransmission mechanism

4.4.1 Sensitivity Analysis

The impact of tuning the k factor was also investigated. As mentioned earlier, the k value can be set according to the reliability requirements. In Figure 4-17, it is shown that as we increase the value of k, the packet success rate decreases. This is because, when k increases, for a fixed PRR value between a sender and its lowest priority relays, the retransmission probability, p_{coor} decreases. Hence, there is less chance that the packet is retransmitted since the sender assumed that the packet had been successfully sent towards the destination, which may be wrong due to the simple way of determining the p_{coor} value.

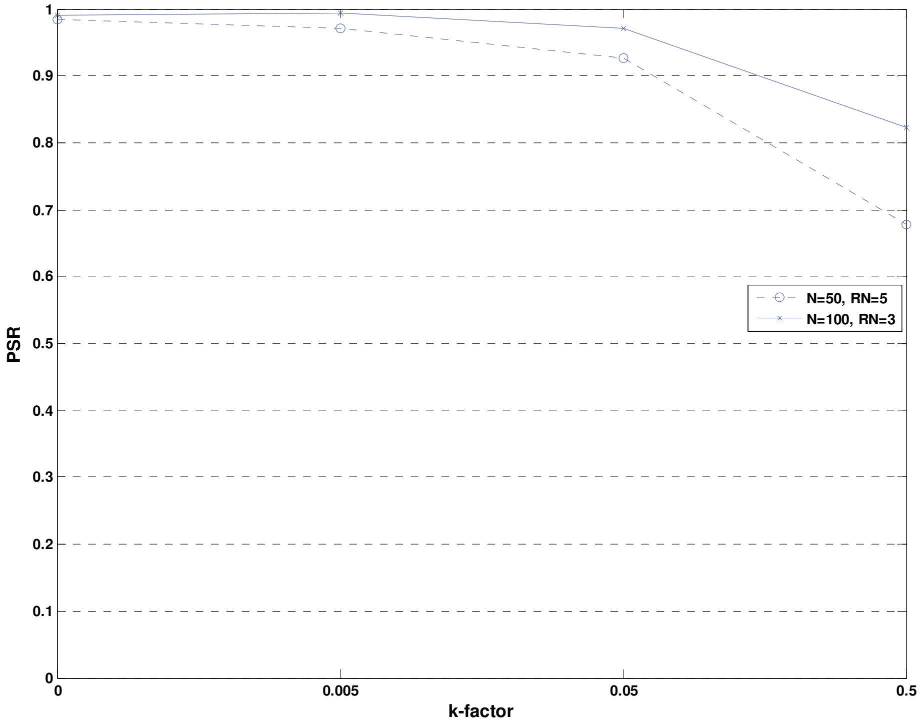

Figure 4-17: Packet success rate versus *k*-factor for network size of 50 nodes with retransmission attempt (RN) =5 and network size of 100 nodes with retransmission attempt (RN) = 3

However, in terms of energy efficiency, as can be seen in Figure 4-18, as we increase the value of k, the efficiency increases due to fewer transmissions being involved for the packet to be successfully received at the destination. Therefore, there is a trade-off between the reliability and the energy efficiency. Basically, with a higher level of reliability, we find that the energy efficiency is lower. In addition, the total energy efficiency for network size of 50 nodes is about 75%-83% more than the efficiency achieved by the network of size 100 nodes. This is mainly due to the increase in the number of communication transmissions and receptions that are to be expected in the denser network.

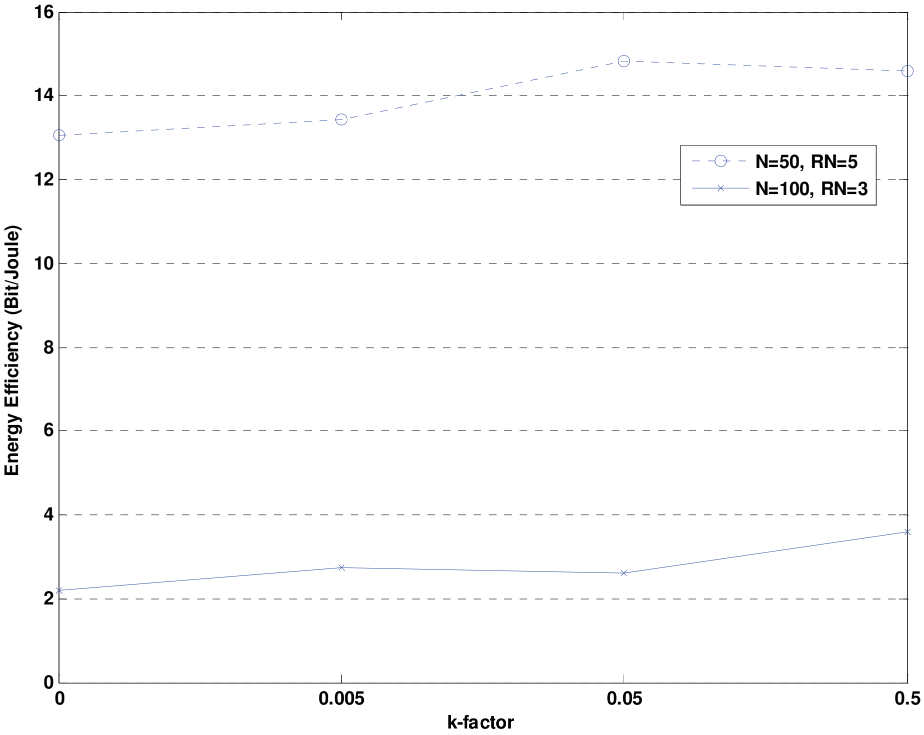

Figure 4-18: Energy efficiency versus *k*-factor for network size of 50 nodes with retransmission attempt (RN) =5 and network size of 100 nodes with retransmission attempt (RN) = 3

4.5 Conclusions

In this chapter, we highlighted our proposed variant of OR for WSNs. Through simulation analysis, we have conducted performance studies of WSNs adopting our variant of OR as their routing protocol. The impact on the variant's performance through the setting up of different values for the MAC and OR parameters was discussed. A general condition in setting up the initial back-off for the MAC protocol and coordination coefficient delay was established to maximize the performance of the OR. In addition, the benefit of adopting the proposed Implicit Acknowledgement coordination scheme was also presented and discussed. Basically, through the Implicit Acknowledgement coordination scheme, the performance of OR can be further improved, especially, if the packet delivery delay is a concern. Finally, we also presented a proposed variant that provides provisional reliability for quality of service in WSN applications.

Chapter 5

Analytical Framework for the Opportunistic Routing Protocol

In this chapter, we propose an analytical framework for performance modelling of the opportunistic routing protocol by combining Markov Chain and standard queueing theories in the context of OR in WSNs. Our goal here is to formulate a framework that can be used to evaluate opportunistic routing performance in a WSN environment. With this framework, the impact of different parameter settings can be studied in order to provide guidelines for network practitioners and system designers. Our focus in this analysis is to model the reliability and end-to-end delay for a single source-destination path through a WSN using OR.

The main contribution of this chapter is our proposal for a comprehensive analytical framework that incorporates a realistic channel model of WSN, MAC model, a queueing model and the coordination cost of opportunistic routing. Since our motivation for applying OR in a scenario where the WSN deployment is via a random deployment of nodes, we cannot guarantee that the hidden terminal problem can be totally avoided - especially when using the CSMA/CA MAC protocol. Although mechanisms such as RTS/CTS exist for such MAC protocols as in IEEE 802.11, it is known that they incur significant overheads [112, 113]. In addition, this mechanism is not implemented in B-MAC and IEEE 802.15.4 [54, 58]. Moreover, often the RTS/CTS scheme does not guarantee to be able to mitigate the hidden terminal problem completely.

We substantially extend our analysis to include realistic characteristics of the CSMA/CA procedure; namely, a collision problem due to hidden terminals arising from the limited carrier sensing range capabilities of sensor nodes. Our proposed framework is different from previous works [22, 101] that have only considered packet transmission errors due to radio shadowing and fading, or having perfect transmission scheduling to avoid collisions due to simultaneous transmissions. In addition, we also approximate the probability of collision at the receiver, due to the hidden terminal problem which is common in systems incorporating randomly deployed nodes and can degrade the overall performance of the routing in CSMA/CA-based wireless networks as reported in [114, 115]. Most of the previous work reported in the literature on OR modelling did not include this problem in their considerations. This effect is relevant in our study due to the nature of the node deployment that is being considered.

In addition, due to our time and priority-based coordination scheme, the issue of failures in the Implicit Acknowledgement scheme can also cause problems concerning the overall performance of OR. As explained in Section 3.1.3, the coordination procedure plays a very important role in ensuring that collisions and packet duplication are minimised. All of the related works assume that this procedure will always be successful and hence it is not incorporated into their models [21-23, 100, 102]. On the contrary, we argue that this is not always true, since the coordination procedure also faces similar problems such as transmission errors, collision, fading and link asymmetry. Therefore, it is important to consider this issue in our framework in order to increase the realism of our model when practical situations are involved. Another point that highlights the difference between our model and those considered by previous researchers is that, since nodes are deployed randomly, the problem of a disjointed CRS also needs to be taken into account. This is a unique consideration compared with the other frameworks that have been proposed.

To model the end-to-end delay performance of OR, we have adopted some standard queueing theory methodologies to determine the expected time that a packet spends at each of the active relays connecting the source and destination nodes. This time, we consider the packet service time, channel access delay and mean coordination delay parameters. Again, with our assumed deployment of nodes in the WSN, some active relay nodes can potentially become points where the same packets converge before being forwarded again onto the next hop. Hence, at these particular nodes, the mean coordination time will be different, depending on the previous hop nodes. As a result, the mean time for coordination will not be constant and needs to be more accurately determined. We have formulated an equation to determine the mean coordination time and this will be discussed in Section 5.3.2.

5.1 System Model

In this section, we discuss the network layout, the radio channel and the medium access scheme models in order to develop the analytical framework for modelling the performance of OR in WSNs.

5.1.1 Network Model

Figure 5-1 illustrates a typical scenario for a wireless sensor network modelled in our study using a source node s, which transmits information to a destination node D via intermediate nodes. The information that is stored at each node regarding its neighbouring nodes is in the form of a tuple $(d_{j_i}, p_{j_i}, d_{j_i,destination})$, where d_{j_i} is the Euclidian distance of the neighbouring node j from node i, p_{j_i} is the packet reception ratio (PRR) that reflects the estimated link quality between nodes i and j and $d_{j_i,destination}$ is the distance of node j from destination node. This information can be determined using a localization operation [32, 33] and probe messages [34, 35] respectively.

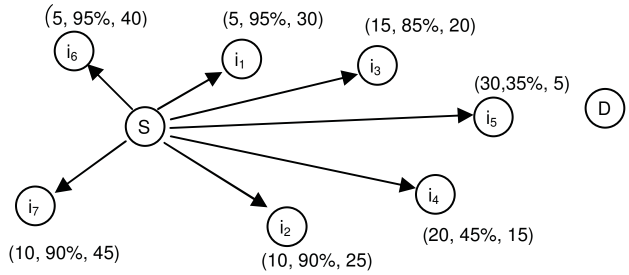

Figure 5-1: A typical scenario in a randomly populated low power wireless sensor network with source node, S, its neighbours ($i_1 - i_7$) and destination node, D.

In this model, we define a set V of $n = |V|$ wireless sensor nodes with a finite queue buffer of size K deployed randomly in a given area and each node is assigned a unique identifier $i = \{1, 2, 3, ..., n\}$. In addition, all sensors transmit on a common carrier frequency using an omni-directional antenna and a fixed transmission power with no duty cycle mechanism. It also operates in half-duplex mode which means that simultaneous transmitting and receiving is not possible.

Based on this topology, the wireless sensor network can be seen as a probabilistic directed graph $G = (V, E, P)$ where $v_i \in V$ denotes a node and an edge $e_{ij} \in E$

represents the communication link between node v_i and v_j with packet reception rate (PRR) determined by $p_{ij} \in P$ which represents a successful packet transmission or, in the other words, the *link quality* through the radio channel between node i and j. In our model, we also assume that for any node in the WSN network, (s_i, d) $\{s_i, d \in V, i = 1, 2, ..n-1\}$ is the pair of nodes representing the source and destination of a packet transmission respectively.

In terms of network load, in our study, we assume that the WSN is dealing with a non-saturated network which is common in low-data rate WSN applications. In addition, analyses of network traffics generated by specific application of WSNs are not conducted in our study. Modelling multi-hop networks that consist of nodes with buffers is challenging since the distribution of the arrival process at the relay nodes is difficult to determine and cannot easily be characterised. Thus, as a first approximation, we model the packet arrival and service rates by approximating them to follow Poisson and Exponential distributions respectively. A similar assumption was made in [25] in terms of packet arrival rate at the source node. Based on this assumption, each node is considered as a queueing system that can be modelled as a standard M/M/1/K system [75]. Basically, our modelling goal is to reach the best trade-off between analytical complexity and accuracy of the results.

5.1.2 Channel Model

In general, a wireless communication is said to be successful if the signal to noise ratio (SNR) for the communication at a distance d is above some threshold value ($SNR \geq \psi$). This value is determined by taking into account the received power at the receiver as well as the noise floor for a particular radio transceiver based on the following expression:

$$SNR(d)_{dB} = P_{t\ dB} - PL(d)_{dB} - P_{n\ dB} \tag{5.1}$$

We assume that the radio propagation follows a lognormal path loss model since this model can be used for large and small coverage area systems [116]. The lognormal path loss model for a radio communication between 2 nodes with a separation distance of d is computed as follows:

$$PL(d) = PL(d_0) + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + \overline{X}(0,\sigma) \tag{5.2}$$

Where d_0 is the reference distance, γ is the path exponent and $\overline{X}$ is a shadow fading factor which is a normal random variable with zero mean and σ standard deviation. Based on the theoretical link layer model for wireless sensor node presented in [40], for standard non-coherent FSK modulation and Manchester encoding scheme with frame size of f bytes and preamble of l bytes, the link quality known as the packet reception rate (PRR) can be expressed in terms of the SNR between two nodes according to the following equation:

$$p(d) = \left(1 - \frac{1}{2}\exp^{-\frac{SNR(d)}{1.28}}\right)^{8(2f-l)} \tag{5.3}$$

The proposed model calculates the PRR such that it takes into consideration the log-normal shadowing radio channel as well as channel modulation and the encoding scheme of the wireless sensor node.

In our study, we assume that the WSN is deployed at isolated places with no interference from other nodes with different types of communication channel (i.e. IEEE 802.11). Hence, links between each node and its neighbours are assumed to be statistically independent channels [37]. We also assume that wireless receptions at different nodes are independent (This has been supported by prior measurements [117]).

Furthermore, we also assume the channel encounters the effects of a Slow Fading Channel in which we assume a packet's successful transmission probability is regarded as approximately constant during the packet's transmission. Figure 5-2 shows the mean PRR between 2 nodes at different distances and with different transmission powers which we have generated, based on the model proposed in [40]. Generally, as the separation distance increases, the PRR will decrease. As expected, for higher transmission powers, the PRR will increase.

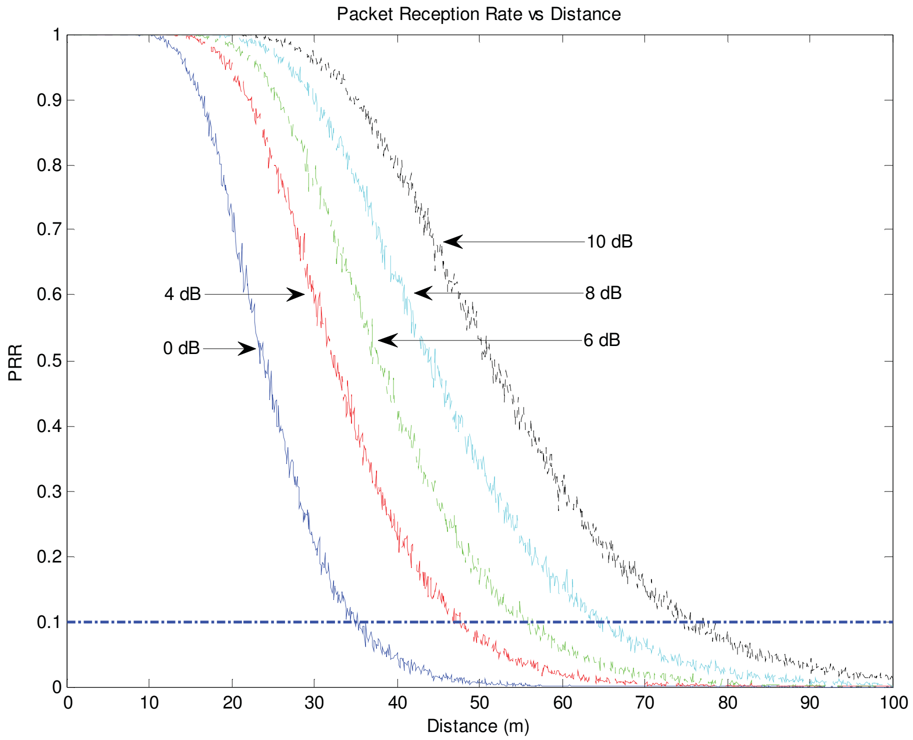

Figure 5-2: Packet reception rate as a function of separation distance for different transmission powers where the path loss exponent $\gamma = 3.5$, the standard deviation of fading $\sigma = 3.8$, frame size (bytes) $f = 50$ and preamble length (bytes) $l = 2$. The horizontal line at PRR=0.1 is the reception threshold value. In this graph, the values are derived from the adopted radio channel model and the Mica2 module.

The distribution of PRR for a successful communication is given by:

$$P\{p(d) \geq \zeta\} \tag{5.4}$$

Where ζ is the threshold value of PRR for a successful connection between two nodes that are separated by a distance d. In our analytical framework, we set the threshold value to be 0.1 and using equation (5.3), with this value, the lower bound for the SNR between any two nodes can be derived as being equal to 7.6 dB. Hence, the cumulative distribution for the lower bound of the SNR is given by:

$$F\{SNR(d) \leq 7.6\} \tag{5.5}$$

We undertook a Monte-Carlo experiment for a pair of nodes separated by a distance d, using a fixed transmission power and noise floor, and we generated 1000 samples of the PRR values based on equation(5.3). By using the statistical tools in Matlab®, (*lognfit* and *logncdf*) we can determine a distribution for the lower bound of the SNR. Hence, according to standard probability laws, the distribution of a successful communication due to the fading effect between two nodes (i.e. a and b) can be derived using the following expression:

$$\Pr(Channel\_success)_{ab} = 1 - F\left\{SNR\left(d\right) \leq 7.6\right\} \tag{5.6}$$

In addition, we assume that the channel is symmetric - which is natural when transmitting and receiving over similar frequencies. Moreover, the communication range is equal to the carrier sensing range of a node. We note that these assumptions are widely adopted as in [118].

5.1.3 Media Access Control (MAC) Model

Since we are assuming that every node shares the same wireless communication channel in order to communicate, in addition to channel failure due to fading, we also need to consider unsuccessful communication due to potential collisions that can occur during packet transmission. With the assumption that every sensor node has a limited buffer size for communication, whenever there is a packet in the buffer, the node will immediately attempt to transmit the packet. We assume that the MAC protocol used in our framework is based on the well-known CSMA/CA protocol due to its simplicity in terms of its implementation and operation. Moreover, this protocol is a basic building block in many media access protocols such as IEEE 802.11, IEEE 802.15.4, SMAC and B-MAC which are commonly used in WSNs.

In our study, we adopted the B-MAC protocol which is similar to IEEE 802.11(Basic Access) or an unslotted IEEE 802.15.4 which does not enforce the RTS/CTS mechanism since operationally, it requires fewer control packets and a shorter delay time. In wireless sensor networks, due to constraints on energy resources, a CSMA/CA that requires less transmission is favoured. Since we are assuming that all sensor nodes share the same channel for communication, the problems of collision and interference are taken into consideration in our analytical framework. In the following sections, we shall discuss the analytical model for the B-MAC. Based on the specifications for B-MAC, we assume that, when each node has a packet to be transmitted, it computes an initial back-off time and waits before sending a packet. After the back-off counter expiration, the node will perform a clear channel assessment (CCA) operation before transmitting the packet. If the channel is sensed to be busy, a congestion back-off time will be computed.

5.1.3.1 Collision Probability

In this section, we shall derive the collision probability that occurs for each node's transmission. In CSMA/CA MAC, the random back-off time is set to avoid simultaneous clear channel assessment that can lead to collisions occurring during transmission and corruption of the packet that is being transmitted. In a non-persistent CSMA/CA with no retransmission, the collision probability is one of the components that will determine the probability of successful communication between two nodes.

There have been many previous works related to the analysis of collision effects in the CSMA/CA MAC protocol for both single hop and multi hop networks [118-121]. In our work, the analytical model to determine the collision probability is based on the one described in [119] and [120]. Note that in those studies, the collision probability was for a single hop network and a homogenous network. Based on this idea, we extended it for a multi-hop network which is the main focus of our study. The approximation is based on the assumption that each packet collides with a constant and independent probability and is also independent of the channel status.

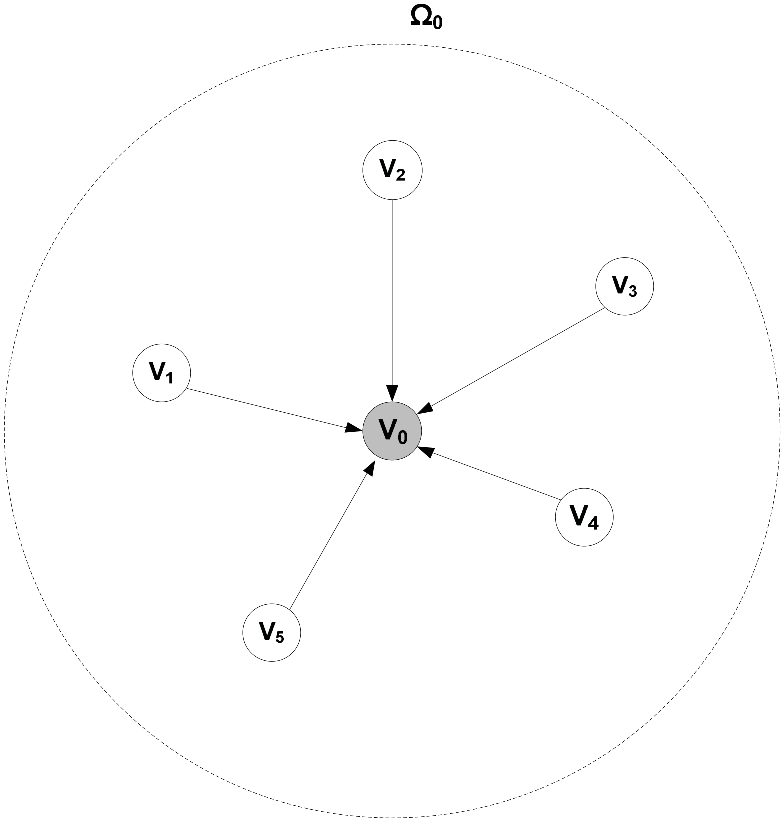

Figure 5-3: Example of a one hop network topology

To assist with the explanation of estimating p, the probability of collision experienced by a packet transmitted on a channel, an example of a single hop network is considered as shown in Figure 5-3. In this topology, we assume that V_0 is the sink node in which all of its neighbouring nodes are sending a packet while V_0 is assumed not to be generating any packet. The big dashed circle indicates the broadcast range for V_0. Furthermore, we assume that transmission by any of the nodes ($V_1 - V_5$) can also be heard by any of the others. We define a neighbourhood set Ω_l of node l which contains all the nodes in the carrier sensing range of V_l. The carrier sensing range contains the set of nodes that can be heard by a node while performing clear channel assessment (CCA) before packet transmission can start. Generally, this operation will determine whether the channel is free from any transmission which also means all neighbours of a particular node are idle. We denote $|\Omega_l|$ as the cardinality of Ω_l and let τ_l be the transmission probability for all nodes in the neighbouring set Ω_l including node V_l.

In our model, based on the B-MAC protocol, when a node has a packet to transmit, it will wait a random guard time similar to the Distributed Inter Frame Space (DIFS) duration used in DCF scheme for IEEE 802.11. After this time, the channel must be sensed as idle. In the event of the channel being busy, the node will need to wait for a random back-off time interval. Back-off time intervals are slotted and their durations are randomly chosen from a range involving the contention window (CW) [0, CW-1] and nodes are only allowed to start their transmission when the counter reaches zero. Hence, if p is the collision probability, then an arbitrary packet is successfully transmitted with probability $1-p$, and the average back-off window of such a packet is $\left(CW-1\right)/2$. If the first transmission fails, the packet is successfully transmitted on the second attempt with probability $p(1-p)$. The average back-off window in this case is $2(CW-1)/2$. This procedure will be repeated until to the last (Kth) permitted attempts. The contention window size for congestion back-off can be fixed, as in B-MAC, or follow the binary exponential multiplier that doubles the size for every attempt as in IEEE 802.11 and 802.15.4 MAC until it reaches the CW maximum value. In the case of IEEE 802.11 and 802.15.4 MAC protocols, the average back-off window for a second attempt in the previous example will be $(2CW-1)/2$.

With the assumption that the collision probability p can be decoupled such that it is constant and independent, the expected back-off window for CSMA/CA MAC can be calculated from:

$$W_{avg} = n\left(\frac{W}{2}\right)+np\left(\frac{\gamma^{1}W}{2}\right)+\ldots+np^{m}\left(\frac{\gamma^{m}W}{2}\right)+np^{m+1}\left(\frac{\gamma^{m}W}{2}\right)+\ldots+np^{K-1}\left(\frac{\gamma^{m}W}{2}\right) \tag{5.7}$$

Where $n=\dfrac{1-p}{1-p^{K}}$ and $(1-p^{K})$ is a normalization term for ensuring a valid probability distribution of each back-off stage. W is the contention window size (in slots), γ is the back-off factor and m represents the maximum back-off stage. If γ equals two, the operation to determine the back-off counter is similar to the binary exponential back-off mechanism that is used in IEEE 802.11 or 802.15.4. If γ equals one, then the back-off contention window is set to be constant for every cycle - which has been adopted in SMAC and B-MAC. These MAC protocols are the commonly used protocols for WSNs with TinyOS [56]. With some algebraic manipulation, equation (5.7) can be represented as:

$$W_{avg} = n\left(\frac{W}{2}\right)\left(\frac{1}{1-p}\right) \tag{5.8}$$

To determine the collision probability due to simultaneous channel access attempts p, we have two different scenarios for the network traffic:

1. Homogenous and Saturated
2. Homogeneous and Unsaturated

In a homogenous network every node has the same packet arrival rate that follows a certain probability distribution such as Poisson. For a saturated network, each node is assumed to always have packets to be transmitted, thus the queue on every node is never empty. In terms of deriving the collision probability, the simplest case will be to assume that we are dealing with a homogenous and saturated network which will be the basic model that we shall use. On the other hand, the homogenous and unsaturated case will increase the complexity of deriving the probability but with some assumptions we can approximate the collision probability.

Note that for both saturated and non-saturated networks, each node will perform the same back-off procedure. In a homogenous and saturated network, the transmission probability, τ_l of a node in an arbitrary slot is given by:

$$\tau_l = \frac{1}{W_{avg}} \tag{5.9}$$

Moreover, for every transmission attempt of v_l node, the probability that its neighbouring nodes are idle can be expressed as:

$$p_{l,idle} = (1-\tau_l)^{|\Omega_l|} \tag{5.10}$$

Hence, the collision probability is then given by

$$p = 1-(1-\frac{1}{W_{avg}})^{|\Omega_l|} \tag{5.11}$$

In terms of a non-saturated network, according to [120], by ignoring the time where the back-off counter is idle due to there being no packets in the queue, the difference between the saturated and non-saturated cases in terms of the mean number of back-off stages in the former is more than the mean number in the latter. Based on this observation, the average attempt rate per slot, $\eta' \left(0 \le \eta' \le 1\right)$ is given as:

$$\eta' = p_a \eta'_c \tag{5.12}$$

where η'_c is the average attempt rate per slot for each node (i.e. the ratio of the number of attempts to the time spent in back-off) on the condition that the buffer is not empty and p_a is the probability on a non-empty buffer.

As a result of the decoupling assumption [122], the collision probability encountered by a node can be expressed in terms of η' as follows:

$$p = 1 - (1 - \eta')^{n-1} \tag{5.13}$$

where n is the number of nodes accessing the same channel. Depending on the type of network that is assumed, equations (5.9) and (5.11) or equations (5.12) and (5.13) establish a fixed point in which the collision probability p can be solved through numerical methods.

In order to complete the fixed point analysis of equations (5.12) and (5.13), η' needs to be expressed in terms of p. In doing so, let $R(p)$ and $X(p)$ be the mean number of attempts and the mean back-off time for every packet transmission respectively. Applying the results in [123] ,the conditional average attempt per slot is given as:

$$\eta'_c = \frac{R(p)}{X(p)} \tag{5.14}$$

where

$$R\left(p\right) = p^0 + p + p^2 + \ldots + p^{K-1} \tag{5.15}$$

$$X\left(p\right) = \frac{W}{2} + p\gamma\frac{W}{2} + p^2\gamma^2\frac{W}{2} + \ldots p^{K-1}\gamma^{K-1}\frac{W}{2} \tag{5.16}$$

In equation(5.16), W is the contention window size, $\gamma(>0)$ is the multiplier of the exponential back-off depending on the MAC protocol type and K is the maximum number of back-off attempts.

Similarly, for p_a, we have assumed that each sensor node has a limited and small buffer which is common for a sensor node. Based on this assumption, let Y_c be the mean service time of a packet on the condition that the buffer is not empty. Hence, we can say that p_a is the probability that at least one packet arrives during the period with duration Y_c. Considering that, on average a node will wait for a back-off time of $X(p)$ for every packet transmission, Y_c can be calculated by:

$$Y_c = X(p) + T_{packet} \tag{5.17}$$

where T_{packet} is the duration of data packet transmission. Assuming that the packet generation rate on a node follows a Poisson distribution, the traffic intensity is $\rho = \lambda Y_c$ where the packet arrival rate of a node is λ. Based on this assumption, the steady-state probability p_a, can be expressed as:

$$p_a = 1 - e^{-\rho} \tag{5.18}$$

Finally, by combining all the previous equations the average attempt rate can be expressed in terms of p as:

$$\eta'(\lambda, p) = (1 - e^{-\rho})\eta'_c \tag{5.19}$$

5.1.3.2 *Channel Access Probability*

In wireless communication over a shared channel, the collision problem is one of the main causes of communication failure. In non-persistent CSMA/CA, a node will drop a packet if the number of attempts to access the channel has reached the prescribed limit. In Figure 5-4, when node V_1 is transmitting a packet to node V_3, all terminals within V_1's transmission range will observe that the channel is busy during the clear channel assessment (CCA) procedure and will back-off for a random time. In the case that node V_2 wants to transmit its packet, it will notice that the channel is busy and wait for a random back-off time. This process will ensure that collisions can be avoided until the channel is successfully accessed to get a successful transmission. For the persistent CSMA/CA protocol, we can assume that the probability of successfully accessing the channel is almost surely equal to 1. On the other hand, for non-persistent CSMA/CA, the probability of successful channel access can be approximated using the following expression:

$$\Pr(CSMA\_success) = 1 - p^{K+1} \tag{5.20}$$

where p is the collision probability encountered by a node which is determined according to equation (5.11) or equation (5.13) and K is the maximum attempts allowed if channel access failure occurs.

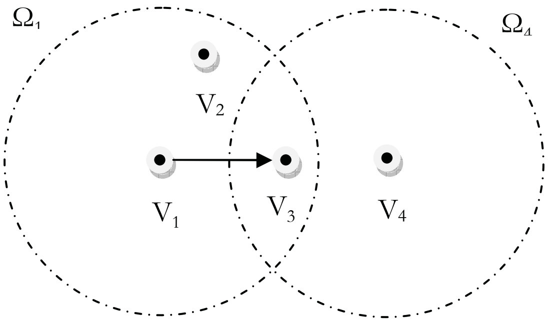

Figure 5-4: Example of WSN topology

5.1.3.3 Interference Probability

In general, interference in wireless communication can cause communication failure even with CSMA/CA MAC. The main reason for this problem can be due to a failure during the CCA operation to sense the busy channel - which commonly occurs in multi-hop networks. This problem is normally known as the hidden terminal problem. Figure 5-5 shows an example of a network with the hidden terminal problem. This problem occurs due to the limited carrier sensing range of a node. Even though there is a procedure that uses RTS/CTS control packets to resolve this problem, it incurs a rather high overhead (40% - 75%) of the channel capacity in sensor networks [54, 124]. Based on the assumption for the wireless channels in our study, the carrier sensing range is the same as the transmission range and is shown in Figure 5-5 by a dashed circle. Therefore, according to the network in Figure 5-5, any transmission by node V_1 will not be sensed by node V_4 during its CCA procedure. Thus, if V_4 has a packet to transmit during a transmission by V_1, it will assume that the channel is idle and start transmitting the packet. As a result, the packet received at V_3 will be corrupted. The duration that can cause interference on a certain node is known as the vulnerable period, T_v. In a similar way to the Basic Access mechanism of IEEE 802.11, the duration of the vulnerable period is claimed to be at least twice that of the data packet transmission duration, T_{packet} [31, 125].

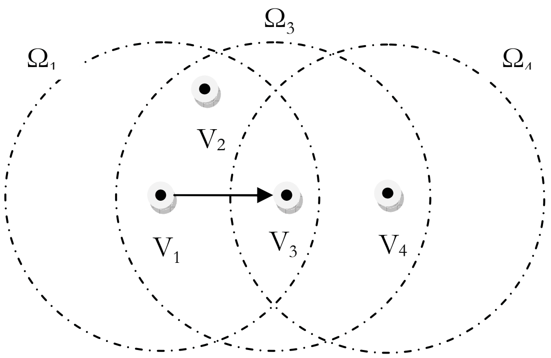

Figure 5-5: An example of topology with the hidden terminal problem. In this network, $\Omega_{3\backslash 1} = \Omega_3 - (\Omega_1 \cap \Omega_3) = \{V_4\}$

To analyse this problem, we derive the probability of collision due to simultaneous transmission of nodes outside the carrier sensing range of a node. Let us define $\mathbf{\Omega}_{a\backslash b} = \mathbf{\Omega}_a - (\mathbf{\Omega}_b \cap \mathbf{\Omega}_a)$ to be the hidden node set that contains all nodes that are within the carrier sensing range of the receiver V_a but do not belong to the carrier sensing node of the transmitter V_b (i.e. $\mathbf{\Omega}_{3\backslash 1} = V_4$ in Figure 5-5). Let I be the event that a collision occurs due to a simultaneous transmission from a hidden node. Thus, the probability of interference occurring on a receiver a for every transmission from b is equivalent to

$$\Pr(I) = 2T_{packet}\left(1 - \prod_{i=1}^{|\Omega_{a\backslash b}|-1} (1-\tau_i)\right) \tag{5.21}$$

where τ_i is the transmission probability of node within the hidden node set. Using(5.21), the probability that no interference will occur can be determined by taking its complement and is given as:

$$\Pr\left(No\ Interference\right) = 1 - \Pr(I) \tag{5.22}$$

5.1.4 Successful Transmission Probability

Finally, using the definitions (5.6), (5.20) and (5.22), we derive a product form to compute the probability of a successful transmission from node a to b as:

$$\begin{aligned} Prob\left(Trans\_success\right)_{ab} = {} & \Pr\left(Channel\_success\right)_{ab} \cap \Pr(CSMA\_success)_a \\ & \cap \Pr\left(No\ Interference\right)_b \end{aligned} \tag{5.23}$$

5.2 Opportunistic Routing Protocol Model

In terms of the OR protocol, the model is based on the variant of OR for WSNs that we proposed in Section 4.1. In order to model the OR in WSN, we need to determine the Candidate Relay Set (CRS) for every node. Basically, according to the network model of WSNs described in Section 5.1.1, each sensor node will first decide the priority of the potential relay nodes based on their distance to a destination node. Next, each node will perform selection procedure to establish their CRS. Finally, once the CRS for each node has been determined, the order and forwarding time of each relay nodes in the CRS will be assigned for the Implicit Acknowledgement coordination procedure.

5.2.1 Multi-hop Network

In multi-hop networks with opportunistic routing (which is, in fact an example of a multipath routing protocol), the traffic load varies according to the routing along the paths even for a flow from a single source node to a destination node. In randomly deployed WSN networks, some nodes may experience heavier traffic due to cross-over paths, hence transmitting more packets. In the case where a packet duplication mechanism is not present, that particular node may transmit more packets unnecessarily. With multi hop networks that focus on a single source case, we can determine the routing graph for the path from the source to its destination nodes. The routing graph can be represented as a switching matrix, (*SM*). The elements of this matrix show the probability that the packet will be transmitted based on the distribution of the traffic flows in the network.

5.3 Analytical Framework of Opportunistic Routing in WSN

In this section, we shall explain the details of the framework that we have developed to model the performance of opportunistic routing in WSNs. The performance metrics that are of interest through this modelling framework are reliability and end-to-end delay.Such results provide insight into the impact of the different OR design choices for WSN performance, as well as providing hints on how to optimally tune the OR parameters. The basis of this framework is developed through adopting theories of Markov Chain based systems with absorbing states and combined with relevant queueing theory. Basically, the information that is required in this framework involves the link quality between the nodes, the location of the sensor nodes, parameter settings for the MAC and OR, and finally, WSN traffic rate.

5.3.1 The Absorbing Markov Chain Model

In our work, the analytical framework is based on a Markov Chain with multiple absorbing states. Recalling the network model described in Section 5.1.1, let us assume that we have a set V of $n = |V|$ wireless sensor nodes and each node is identified based on its unique identifier number referred to as i where $i = \{1, 2, ..., n\}$. We also denote the identifier for the destination node as $i_{destination} = n$. Thus, the OR routing process for a given flow between any node and the destination node is modelled as an absorbing Markov Chain (MC) in which the nodes represent the set of states, $s_i \in S$ and a *normalised* transitional probability matrix D where each element $d_{s_i, s_j} \in D,\ (i, j) = 1, 2, ..., n-1$ represents the transition probability of sensor node j being selected as a forwarder for a transmission from node i.

The absorbing states correspond to the destination node n (s_n), dead-end nodes $a \in A, A \subset V$ (s_a) and unsuccessful receptions (s_{n+1}). A is a subset that consists of dead-end nodes. A dead-end node is established when the sensor node cannot forward any packet that it has received due to an empty CRS set. When this occurs it will drop any packet that it has received. The absorbing state for unsuccessful receptions (s_{n+1}) represents the loss event where there has been a failure of communication between each node to all of its CRS nodes.

Hence, for every node i with a set of ordered candidate relays of size m, $c_i(l)$, $\{l = 1,2,...,m\}$, destination node (n), unsuccessful state ($n+1$), dead-end nodes (a) and the assumption of independent delivery probabilities (p) based on equation (5.23) between nodes, the transitional probabilities for matrix D are given by:

$$d_{s_i,s_{n+1}} = \prod_{k=1}^{|c_i|}\left(1 - p_{i,c_i(k)}\right), i = 1,2,..,n-1 \tag{5.24}$$

$$d_{s_i,s_j} = p_{i,j}, \quad j = c_i(1) \tag{5.25}$$

$$d_{s_i,s_j} = p_{i,j} \times q_j(l), \qquad j = c_i(l), l = 2,..,m \tag{5.26}$$

$$q_j(l) = \min(1, \left(\prod_{k=1}^{l-1}\left(1 - p_{i,c_i(k)}\right) + \prod_{r=1}^{l-1}\left(1 - p_{c_i(r),j}\right)\right) \tag{5.27}$$

$$d_{s_n,s_n} = 1, \qquad d_{s_{n+1},s_{n+1}} = 1 \qquad d_{s_a,s_a} = 1 \tag{5.28}$$

Equation (5.24) is the transitional probability of unsuccessful transmission from node i to all candidate relays. Equations (5.25) and (5.26) are the probabilities of the highest priority and lower priority candidate relays to get selected as the packet forwarder respectively. Equation (5.27) is the probability that the higher priority node fails to receive the packet successfully or of coordination failure among the relays in the CRS. The *minimum* function in equation (5.27) is required in order to ensure a valid probability distribution. Finally, expressions in equation (5.28) denote absorbing states of the destination node, failure states and dead-end nodes respectively.

Based on the theory of Markov Chains with absorbing states [76], the reliability of a WSN that adopts Opportunistic Routing can be determined from the fundamental matrix F as derived from

$$F = \left(I - D^{(n-1-|A|)\times(n-1-|A|)}\right)^{-1} \tag{5.29}$$

To ensure that the correct fundamental matrix is derived, the matrix D must be in its *Canonical form* as in (5.30), where I is the $(|A|+2)\times(|A|+2)$ identity matrix, Q is an $(n-1-|A|)\times(n-1-|A|)$ matrix for all transient states corresponding to nodes in a WSN and R is an $(n-1-|A|)\times(|A|+2)$ matrix for absorbing states.

$$D = \begin{pmatrix} Q & R \\ 0 & I \end{pmatrix} \tag{5.30}$$

From F, the reliability performance of a WSN measured as a packet success rate (PSR) for a routing flow between node i and the destination node n is given by:

$$PSR_{i,n} = \sum_{j=1}^{n-1-|A|} f_{i,j} r_{j,n}, \quad r \in \mathrm{R}, \quad f \in F \tag{5.31}$$

The transitional probability matrix D, can also be used to determine the expected number of hops encountered by every packet from the source in order to reach the destination. Basically, in discrete MCs, matrix D gives the transition probability of a packet flow from each state (node) to every other state (node) in a single period. If we assume that every period represents a hop count, then the *h*-step transition probability $d^{(h)}_{s_i,s_j}$ is the probability that a packet is at node j after h hops given that it originated from node i . The probability of $d^{(h)}_{s_i,s_j}$ can be computed using the Chapman-Kolmogorov (C-K) equations which can be written in matrix notation as:

$$D^{(h)} = DD^{(h-1)} \tag{5.32}$$

Based on equation (5.32), assuming that the source node is node i , the probability of a packet reaching the destination node (n) and failure state $(n+1)$ after h hops $f(h)$ can be determined as the followings:

$$f(h)_{i,n} = d^{(h)}_{s_i,s_n} - \sum_{l=1}^{h-1} f(l)_{s_i,s_n} \tag{5.33}$$

$$f(h)_{i,n+1} = d^{h}_{s_i,s_{n+1}} - \sum_{l=1}^{h-1} f(l)_{s_i,s_{n+1}} \tag{5.34}$$

Hence, the conditional expectation of the number of hops required for a packet from the source node to reach the destination node is given as:

$$E[X_{i,n} \mid Y_{i.n} = success] = \frac{\sum_{h=1}^{H} hf(h)_n}{Pr(Y_{i,n})} \tag{5.35}$$

where H is the limit of the hop count determined when the cumulative probability of hop count is one (i.e. $F(h \leq H) = 1$), $f(h)_n$ is the density probability of reaching the destination node successfully in h hop, $X_{i,n}$ is the number of hops to reach the destination node n from source node i and Y is the event that the packet reaches the destination successfully and $Pr(Y_{i,n})$ is the probability of event Y occurs.

5.3.2 Queueing Model

To determine the mean time a packet spends at each relay node before reaching the destination, we derive an expression that consists of the packet service time, the channel access delay and the coordination delay. Essentially, each sensor node in the network is modelled as a single queue of length K (M/M/1/K) with its total sojourn time defined as:

$$T_i = T_{q_i} + \overline{X_i} \tag{5.36}$$

where T_{q_i} and $\overline{X_i}$ are the mean waiting time in a queue and node service time respectively.

The service time $\overline{X_i}$, is defined as the expected service time to complete any packet transmission request from node i and is given as:

$$\overline{X_i} = T_{pkt} + \overline{B_i} + \overline{CO_i} \tag{5.37}$$

where T_{pkt} is the packet service time, $\overline{B_i}$ is the mean channel access time and $\overline{CO_i}$ is the mean waiting time for coordination procedure.

The mean channel access time, $\overline{B_i}$ is derived from equation (5.7). For the mean coordination waiting time, with the random deployment approach, there is the possibility that cross-over of traffic occurs as shown in Figure 5-6. In this situation, a node can become a common candidate relay (e.g. P2) for multiples nodes with different priorities. Hence, the expected mean coordination time for that particular node needs to be determined by taking into account the probability of itself being selected as the next forwarder and the chosen priority. We denote $\underline{p}_i$ as the vector of probabilities of node i being selected as the next forwarder if it received a packet from nodes that have selected the node i as one of their candidate relays and the number of nodes that consider the node i as their candidate relays is $\left|\underline{p}_i\right|$. The corresponding coordination delay based on the priority of the current node and packet arrival rates from downstream relays are expressed as vectors $\underline{\omega}_i$ and $\underline{\lambda}_i$ respectively. Based on these vectors, the mean coordination time is calculated as:

$$\overline{CO_i} = \sum_{l=1}^{\left|p_i\right|} \underline{p}_i(l)\underline{\lambda}_i(l)\underline{\omega}_i(l) \tag{5.38}$$

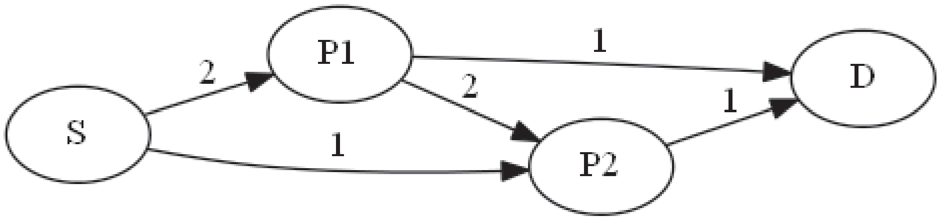

Figure 5-6: Example of a simple WSN topology. The label for each link indicates the priority level of the receiver with respect to the sender. The lower the value the higher the priority level.

In order to determine total packet arrival rates for all nodes within a network, let $\overline{\lambda}$ be the vector of total packet arrival rates for all nodes in the network which can be determined based on the expression below [126]:

$$\overline{\lambda} = \gamma\left(I - W\right)^{-1} \tag{5.39}$$

where $\gamma = (\gamma_1, \gamma_2, ..., \gamma_n)$ denotes the vector of packet generation rates for each node, I is an identity matrix and W is the switching matrix. Note that, the subscript number in the vector represents the ID for each node. For a single active flow in a multi-hop WSN from source node ($i = 1$) to destination node n, $\gamma = (1_1, 0_2, ..., 0_n)$.

In terms of switching matrix W, it is derived based on transitional matrix D according to the following expressions:

$$W = D^{n \times n} \tag{5.40}$$

$$w_{i,j} \in W, \qquad (i, j = 1, 2, .., n-1) \tag{5.41}$$

$$w_{n,n} = 0, \quad w_{a,a} = 0 \tag{5.42}$$

To determine T_{q_i} using Little's law [127], the mean waiting time in a queue at node i can be computed as:

$$T_{q_i} = \frac{L_{q_i}}{\lambda_i} \tag{5.43}$$

$$L_{q_i} = \frac{\rho^2 \left[(K-1)\rho^K - K\rho^{K-1} + 1 \right]}{(1-\rho)(1-\rho^{K+1})} \tag{5.44}$$

$$\rho = \lambda_i \overline{X_i} \tag{5.45}$$

Finally, based on the estimated total node's total sojourn time, the mean end-to-end delay between node i and n can be calculated using the following expression:

$$E\left[Delay_{i,n}\right] = \frac{\underline{T}_i}{(1-d^{1}_{s_i,s_{n+1}})} + \sum_{h=1}^{C} \frac{\sum_{j=1}^{n} d^{(h)}_{s_i,s_j} \underline{T}_j}{(1-d^{(h+1)}_{s_i,s_{n+1}})} + \sum_{h=C+1}^{H} \sum_{j=1}^{n} d^{(h)}_{s_i,s_j} \underline{T}_j \tag{5.46}$$

where $\underline{T}$ is a column vector of expected sojourn times for all nodes in the network, C is the limit of the hop count determined when the cumulative probability of the hop count is zero (i.e. $F(h \leq C)_{i,n} = 0$) and H is the limit of the hop count determined when the cumulative probability of the hop count is one (i.e. $F(h \leq H)_{i,n} = 1$). In equation

(5.46), the first two components represent the conditional expectation of the per hop delay from the source node for up to C hops.

5.4 Illustration of the usage of the analytical framework of OR

To illustrate the use of the proposed analytical framework for a WSN, we consider an example of a WSN with 15 randomly deployed nodes in a region of interest of size 50 x 50 m^2 as shown in Figure 5-7. Based on the assumptions of the network model described in Section 5.1.1, in this example, the source node generates packets according to a Poisson distribution with a mean rate of 1 packet per second. In terms of the parameters for the MAC and OR, the contention window for the *Initial_Backoff* is set to be [50, 80] while the OR coordination coefficient delay, $T_{\alpha} = 25\, ms$. Based on the prioritisation and selection procedure of OR, Figure 5-8 highlights the connectivity tree involving all the selected active relays for a routing flow from source node (1) to destination node (15). In addition, the link qualities which are derived based on equation (5.6) and priority levels between nodes and their candidate relays are also shown in the figure.

Once the information from Figure 5-8 is available, the probabilities for the transitional matrix of the WSN can be derived based on equations (5.24)-(5.28).Note that, in this example, a dead-end node does not exist. Hence, the transitional matrix illustrated in Table 5-1 is already in its *canonical form* where the blue, yellow and orange sub matrices represent the Q , R and I matrices respectively according to matrix expression in (5.30). From the transition matrix, we can derive the fundamental matrix as shown in Table 5-2.

To estimate the mean time every packet will spend on active relay nodes before reaching the destination nodes, the expected sojourn time for each node is calculated using equation (5.36). Thus, in this example of WSN, the expected sojourn time for every active relays is shown in Table 5-3.

In Table 5-4 and Figure 5-9, the density probabilities (PDF) of a packet reaching the destination or encounter communication failure after h counts are shown. Basically, these probabilities are determined from the transitional matrix according to equation

(5.32). Furthermore, we can also observe that the cumulative probabilities (CDF) of the hop count for this network where the probability of a packet to reach destination after 5 hop counts is one ($F(h \leq 5) = 1$).

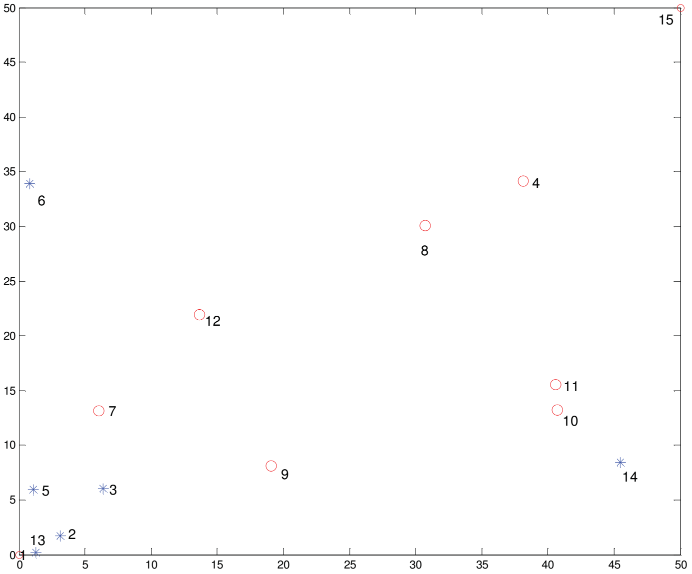

Figure 5-7: Example of random WSN using OR with 15 nodes in an area of 50m x 50m. The active nodes for a routing flow from source node (1) to destination node (15) are all marked as red circle.

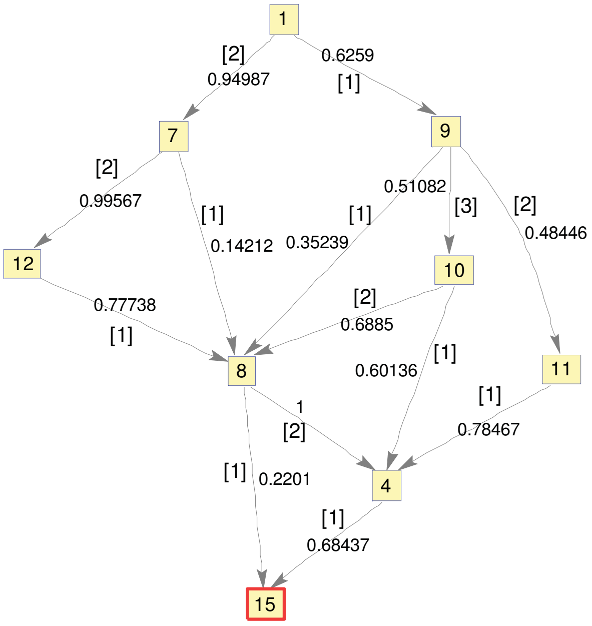

Figure 5-8: The connectivity tree from source node to the destination based on OR protocol. In this diagram, the candidate relays for each node are displayed with their associated link quality and priority level.

Table 5-1: Transitional Matrix in canonical form. N1-N15 represents the nodes in the WSN and FS represents state for unsuccessful communication between a particular node and all its candidate relays.

	N 1	**N 2**	**N 3**	**N 4**	**N 5**	**N 6**	**N 7**	**N 8**	**N 9**	**N 10**	**N 11**	**N 12**	**N 13**	**N 14**	**N 15**	**FS**
N 1	0	0	0	0	0	0	0.323	0	0.656	0	0	0	0	0	0	0.021
N 2	0	0	0	0	0	0	0	0	0.427	0	0	0.521	0	0	0	0.052
N 3	0	0	0	0	0	0	0	0	0	0	0	0.856	0	0	0	0.144
N 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.743	0.257
N5	0	0	0	0	0	0	0	0	0.281	0	0	0.677	0	0	0	0.042
N 6	0	0	0	0	0	0	0	0.156	0	0	0	0.742	0	0	0	0.102
N 7	0	0	0	0	0	0	0	0.156	0	0	0	0.808	0	0	0	0.036
N 8	0	0	0	0.750	0	0	0	0	0	0	0	0	0	0	0.222	0.028
N 9	0	0	0	0	0	0	0	0.400	0	0.140	0.369	0	0	0	0	0.091
N 10	0	0	0	0.646	0	0	0	0.273	0	0	0	0	0	0	0	0.080
N 11	0	0	0	0.816	0	0	0	0	0	0	0	0	0	0	0	0.184
N 12	0	0	0	0	0	0	0	0.813	0	0	0	0	0	0	0	0.187
N 13	0	0	0	0	0	0	0	0	0.478	0	0	0.392	0	0	0	0.130
N 14	0	0	0	0.299	0	0	0	0	0	0	0.673	0	0	0	0	0.028
N 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
FS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 5-2: Fundamental matrix of the analytical framework.

	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14
N1	1	0	0	0.669	0	0	0.323	0.550	0.656	0.092	0.242	0.261	0	0
N2	0	1	0	0.626	0	0	0	0.611	0.428	0.060	0.158	0.521	0	0
N3	0	0	1	0.522	0	0	0	0.696	0	0	0	0.856	0	0
N4	0	0	0	1	0	0	0	0	0	0	0	0	0	0
N5	0	0	0	0.615	1	0	0	0.674	0.281	0.039	0.104	0.677	0	0
N6	0	0	0	0.569	0	1	0	0.759	0	0	0	0.742	0	0
N7	0	0	0	0.610	0	0	1	0.813	0	0	0	0.808	0	0
N8	0	0	0	0.750	0	0	0	1	0	0	0	0	0	0
N9	0	0	0	0.720	0	0	0	0.438	1	0.140	0.369	0	0	0
N10	0	0	0	0.851	0	0	0	0.273	0	1	0.000	0	0	0
N11	0	0	0	0.816	0	0	0	0	0	0	1	0	0	0
N12	0	0	0	0.610	0	0	0	0.813	0	0	0	1	0	0
N13	0	0	0	0.583	0	0	0	0.528	0.478	0.067	0.176	0.392	1	0
N14	0	0	0	0.848	0	0	0	0	0	0.000	0.673	0	0	1

Table 5-3: The mean sojourn time of every active node for a flow from the source node (1) to the destination node (15).

	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14
Service Time	0.0119	0	0	0.0276	0	0	0.0372	0.0129	0.0118	0.0621	0.0370	0.0371	0	0

Table 5-4: **PDF and CDF of hop counts.**

Hop Count	**Probability of Successfully Reaching the destination (N15) in h hops (S)**	**Probability of Reaching the Failure State (FS) in h hops (F)**	**Total Probability**	**Cumulative Probability (S&F)**
1	0	0.020859	0.020859	0.020859
2	0	0.071423	0.071423	0.092282
3	0.06922	0.10943	0.17865	0.27093
4	0.41799	0.13278	0.55077	0.82190
5	0.13237	0.04573	0.1781	1
6	0	0	0	1
7	0	0	0	1
8	0	0	0	1
9	0	0	0	1
10	0	0	0	1

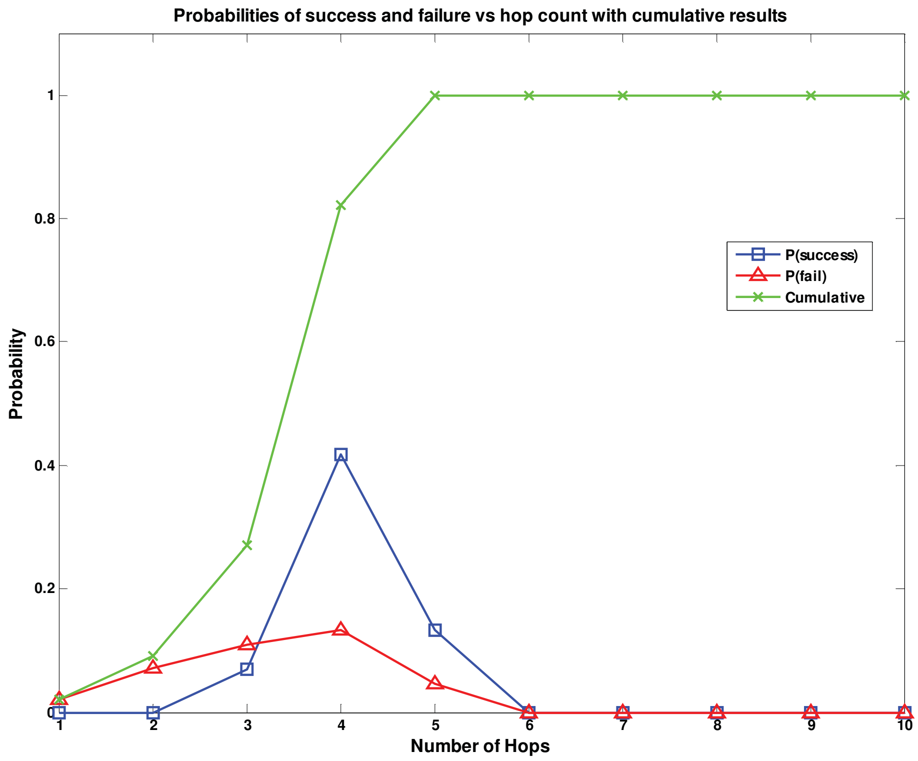

Figure 5-9: Probabilities of success and failure of a packet to reach destination after different number of hops.

Based on all the information that has been calculated thus far, the performance of WSN using OR in terms of the expected reliability, end-to-end delay and number of hops required for a packet to reach the destination from the source node can now be modelled using equation (5.31), (5.46) and (5.35) respectively. The performance results of the WSN calculated using the analytical framework is depicted in Table 5-5. In addition, as a comparison, results obtained from simulation analysis are also shown.

Table 5-5: The performance results.

	Model	**Simulation**	**Error (%)**
RELIABILITY	0.620	0.615	0.81%
END-TO-END DELAY (s)	0.084	0.085	1.11%
HOP COUNTS	4.10	4.0269	1.86%

5.5 Numerical Results

In this section, we present the numerical results from our analytical framework. In addition, we also perform simulation studies to validate the analytical framework that we have proposed. The performance metrics that we are investigating by using the analytical framework and simulator are *packet success rate* and *end-to-end delay* for ad-hoc WSNs. In addition, we also compare the results determined using the proposed framework against other previous frameworks of OR in the literature such as in [21, 22] which we denote as *Model-Perfect Coordination* in this study.

5.5.1 Simulation Setup

The simulation analysis is performed using Prowler [106, 107] which incorporates important models for wireless sensor networks based on Mica2 mote platform which has a data rate of 38.4kpbs at 915Mhz. As mentioned in Section 4.2, in Prowler, realistic wireless channel and media access control (MAC) models have been provided. In addition, OR is implemented in Prowler by taking into account the main procedures involved in its operation, viz: prioritization, selection and coordination. Moreover, packet duplication detection mechanisms to handle the situation when the coordination procedure has failed have also been implemented. Basically, this mechanism will prevent any duplicated packet from being continually forwarded to the destination once it is detected by the relay nodes. Table 5-6 shows the parameters used in the simulation and the analytical framework.

Table 5-6: Simulation parameters

Parameter	Values
Path loss exponent, γ	3.5
Log-normal shadowing variance, σ	3.8
Link Quality Threshold, ζ	0.1
Receiver Sensitivity	-105 dBm
Transmission Power	6 dBm
Packet Length	400 bits
Coordination Coefficient Delay, T_{cc}	25ms
Initial Backoff Contention Window, CW	[50 80] slots
Retransmission Limit	0

In this analysis, nodes are randomly placed within a region of interest (ROI) of size (50 x 50 m^2) and (100 x 100 m^2). For each ROI, we measure the performance of the WSN for different node densities. The results are averaged over 5 runs with 10 topologies that we randomly generated for every network density. We fixed the source and destination nodes so that they are located at the lower left corner and upper right corner of the ROI respectively. We set the simulation time to be 300 seconds to ensure the network reaches steady state in terms of packet success rate and end-to-end delay with the source node generating packets based on Poisson distribution with a mean rate of 1 packet per second. To achieve sufficient statistical confidence in validating the framework, we have adopted the use of the T-test tool.

From Figure 5-10 we observe that the packet success rate of WSN with OR for different numbers of nodes calculated using our analytical framework are within the 95% confidence limit with the simulation results for all densities. In addition, small discrepancies were observed between our proposed model and the simulation since our model does not take into account the packet duplication mechanism that is present in the simulator. Thus, the occurrence of packet duplication due to imperfect coordination is not suppressed in the model. This explains a slightly better reliability modelled by our framework as compared to the simulation results. As can be seen, as the number of nodes increases, the packet success rate also increases. This is due to the fact that more nodes are available to relay the packets through these nodes towards the final destination node. However, the packet success rate will begin to reach a saturation point as we increase the number of nodes. The main reason for this observation is due to the increase in the network traffic that can contribute to an increase in the number of collisions.

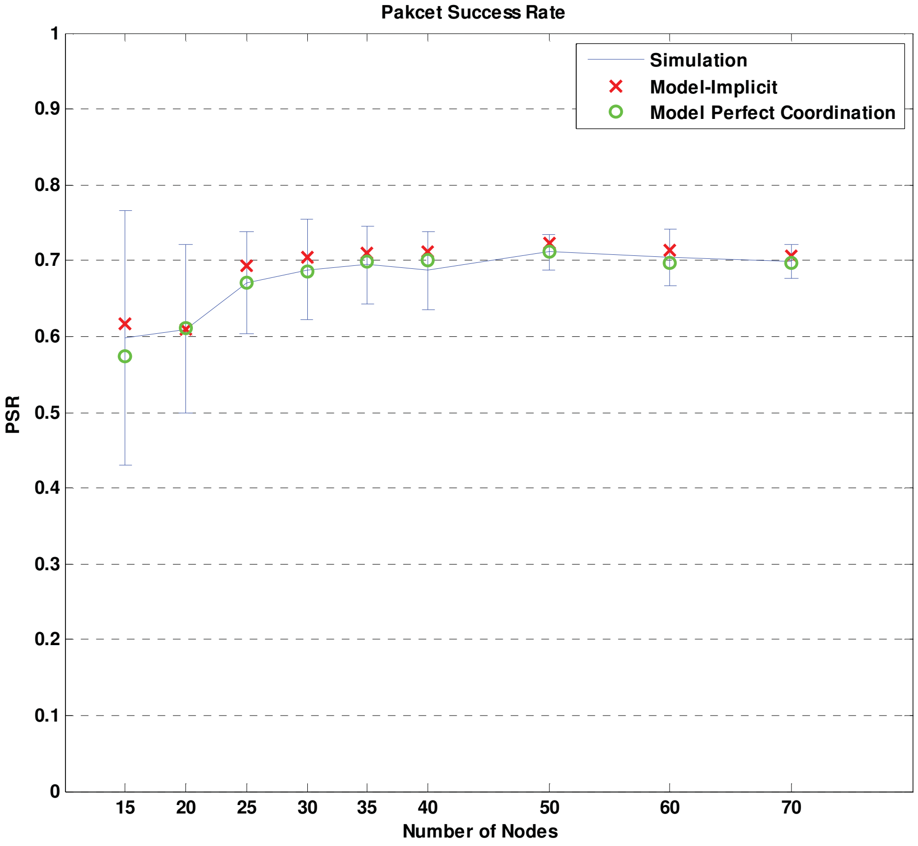

Figure 5-10: Packet Success Rate versus number of nodes in area of (50m x 50m). The minimum *Initial_Back-off* time = 1.3 ms, the minimum *Congestion_Back-off* time = 1.3 ms.

In Figure 5-11, the reliability performance of WSN with OR within a bigger region of interest is highlighted. In terms of the effect of increasing the number of nodes, a similar trend was observed as in the earlier scenarios with a smaller area size. We can see that the reliability of a WSN with OR improves as the number of nodes increases. In addition, from Figure 5-11 it is also shown that the packet success rates derived with our analytical framework are within the 95% confidence limits for all cases as compared to the previous framework. In terms of discrepancies between our model and simulation, as for higher values, this is due to packet duplication from imperfect coordination. Whereas, for the smaller value observed when the number of nodes is 140, this is mainly due to a higher interference probability approximated in the framework due to our homogeneity traffic assumption. We can see that for a model that assumes perfect coordination no packet duplication is present. Hence, the reliability performance predicted by this model is consistently below the simulation results. These results validate the correctness of our framework in terms of modelling the reliability performance of WSN with OR.

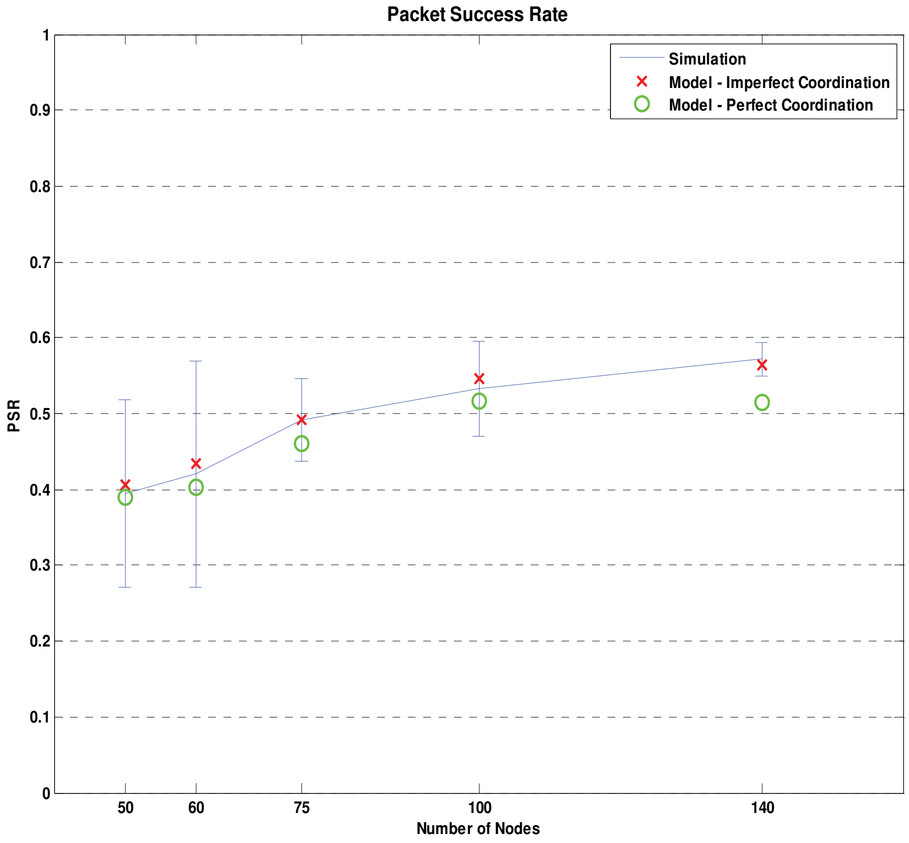

Figure 5-11: Packet Success Rate versus number of nodes in area of (100m x 100m). The minimum *Initial_Back-off* time=1.3 ms, the minimum *Congestion_Back-off* time = 1.3 ms.

In terms of end-to-end delay, from Figure 5-12, we can see that for an ROI size of 50 x 50 m^2, the analytical model that incorporates the imperfect coordination predicted delays closely match with the simulation results when compared to the model that assumes perfect coordination. Due to higher probabilities of packet duplication to occur, the overall network traffic will be higher. As a result, the channel access delay will be higher. This explains the observation with regards to slightly overestimated end-to-end delay modelled by our framework. For a larger ROI size of 100 x 100 m^2, Figure 5-13 highlights the end-to-end delay modelled using the framework with imperfect and perfect coordination cases. We can observe that our proposed framework achieves better accuracy when we compare it to the simulated analysis than the previous works by incorporating the imperfect coordination factor even though the delays are consistently longer due to reasons explained earlier. Note that, even though there are slight discrepancies between our proposed framework and the simulation results, the predicted delays are all within the 95% confidence limit.

In addition, we can see that the delay reaches a maximum when the number of nodes is equal to 25 nodes and 75 nodes for ROI sizes of 50 x 50 m^2 and 100 x 100 m^2 respectively. Basically, we can observe that there is a maximum delay experienced by all packets as we increase the number of nodes in the network. In Table 5-7 and Table 5-8, the average value of the number of nodes in the candidate relay set for each node in the network, the expected number of highest priority nodes traversed by each packet for a flow from source to destination and the average PRR value between these nodes are listed. As can be seen, as we increase the density, the average number of nodes in the CRS ($E[CRS]$) for each node remains almost the same. This is due to the *EPAEC* metric that determines the maximum ratio of expected packet advancement to the total energy consumption in the set. In addition, we also observe that as the number of nodes increases, the expected number of highest priority nodes involved in the flow from source to destination increases until it reaches a maximum value and then decreases. This value implicitly indicates the maximum number of hops each packet will encounter if all the highest priority nodes were able to successfully receive and forward the packet to the destination. In terms of the mean PRR between these highest priority nodes, the value increases as the number of nodes in the network increases. For each number of nodes in the network, based on the values of (A) and (B) in Table 5-7 and Table 5-8, we can approximate the maximum number of hops that each packet will traverse before reaching the destination and the chances of following the path along the highest priority nodes. Based on these observations, we define a metric known as *Hops per Packet success rate (link quality) (HPP)* which is the ratio of the number of highest priority nodes to the link quality between these nodes. Using this metric, we can determine the number of nodes that will give the maximum end-to-end delay. Basically, the network with the highest ratio of HPP will have a maximum end-to-end delay which for 50x50 m^2 area size, the network density of 0.01 (25 nodes) have a maximum average end-to-end delay as shown in Figure 5-14 (a). For 100 x 100 m^2 area size, the network density of 0.0075 (75 nodes) have a maximum average end-to-end delay as shown in Figure 5-14 (b).

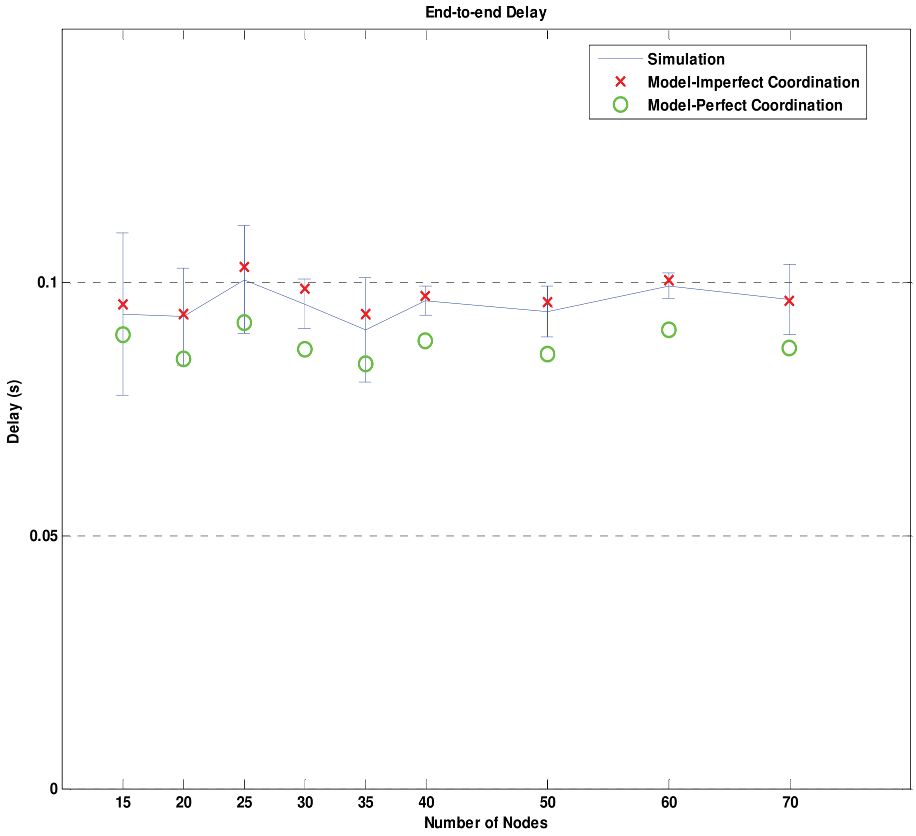

Figure 5-12: End-to-end delay vs. number of nodes in an area of 50m x 50m. The minimum *Initial_Backoff* time=1.3 ms, the minimum *Congestion_Backoff* time= 1.3 ms.

Table 5-7: The observation of the CRS size, mean number of highest priority nodes and mean PRR between these relays. Region of interest area size = 50 x 50 m^2

Number of Nodes (Density)	E[CRS size]	E[Number of highest Priority Nodes from Src-Dest] (A)	E[PRR of the highest Priority relay] (B)
15 (0.006)	1.9	2.76	0.47
20 (0.008)	1.8	3.45	0.54
25 (0.01)	1.8	4.11	0.55
30 (0.012)	1.8	3.40	0.57
35 (0.014)	1.8	3.42	0.60
40 (0.016)	1.8	3.42	0.58
50 (0.02)	1.8	3.42	0.61
60 (0.024)	1.8	3.52	0.61
70(0.028)	1.8	3.54	0.61

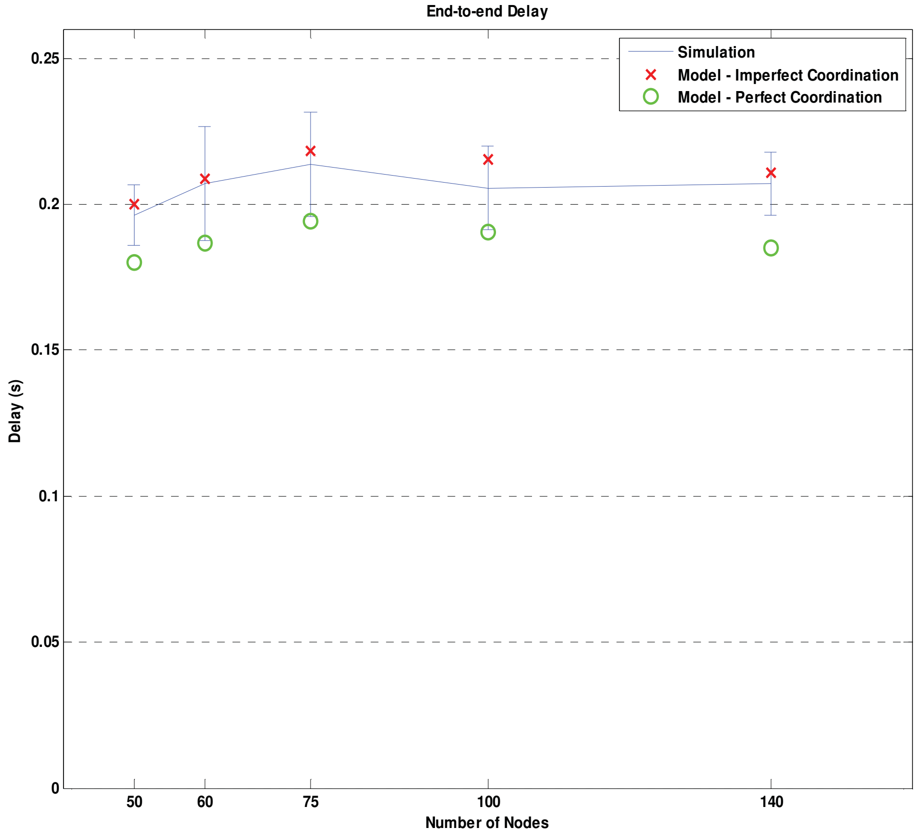

Figure 5-13: End-to-end delay versus number of nodes in an area of 100m x 100m. The minimum *Initial_Backoff* time = 1.3 ms, the minimum *Congestion_Backoff* time = 1.3 ms.

Table 5-8: The observation of the mean CRS size, mean number of highest priority nodes and mean PRR between these relays. Region of interest area size = 100 x 100 m^2.

Number of Nodes (Density)	E[CRS size]	E[Number of highest Priority Nodes from Src-Dest] (A)	E[PRR of the highest Priority relay] (B)
50 (0.005)	1.9	8.06	0.53
60 (0.006)	1.9	8.54	0.54
75 (0.0075)	2.0	8.9	0.53
100 (0.01)	1.9	8.24	0.55
140 (0.014)	2.0	8.24	0.54

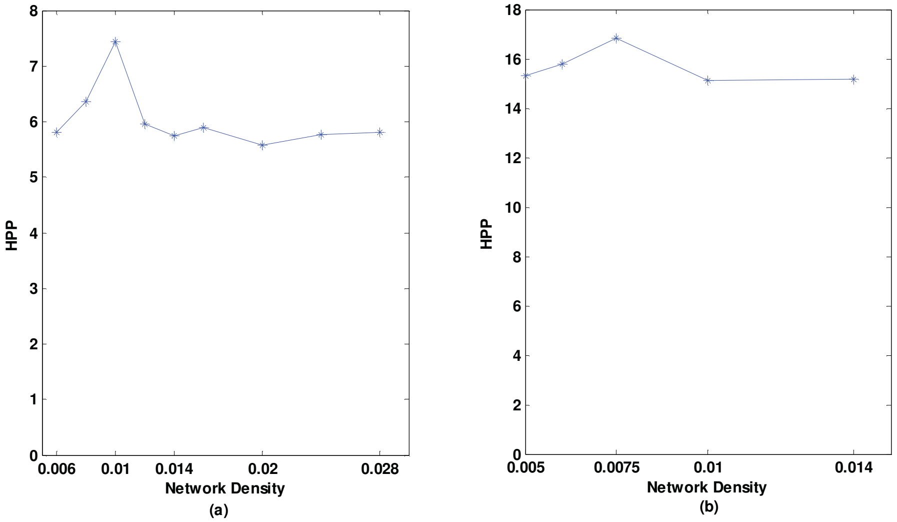

Figure 5-14: Ratio of average number of hops of the highest priority node path to the link quality (PRR) along the source to the destination path. (a) ROI=50 x 50 m^2, (b) ROI=100 x 100 m^2.

In Figure 5-15 and Figure 5-16, we show the expected number of hops required to reach the destination from the source for different numbers of nodes with different region sizes in the network. As can be seen, the number of hops that each packet will encounter to reach the destination node using the proposed framework is comparable with the simulation results as well as within the 95% confidence limits.

In Figure 5-17 and Figure 5-18, the reliability and end-to-end delay of OR for different numbers of nodes in the network are shown respectively. In this evaluation, the minimum *Initial_Backoff* time and *Congestion_Backoff* time intervals for the B-MAC protocol were both increased to be 2.5 ms. It is observed that, in terms of packet success rate, both models are within the 95% confidence interval of the simulation results leading to the conclusion that we have validated our analytical model. For end-to-end delay, in Figure 5-18 we can see that our proposed framework, that incorporates coordination failure, achieves better accuracy for the number of nodes involved in the network as compared to the perfect coordination procedure. To validate the correctness of the HPP metric in determining the set with the maximum end-to-end delay, either the simulation or the analytical framework can be used. As illustrated in Figure 5-18, the number of nodes that gives the maximum end-to-end delay coincides with the set determined using the HPP metric.

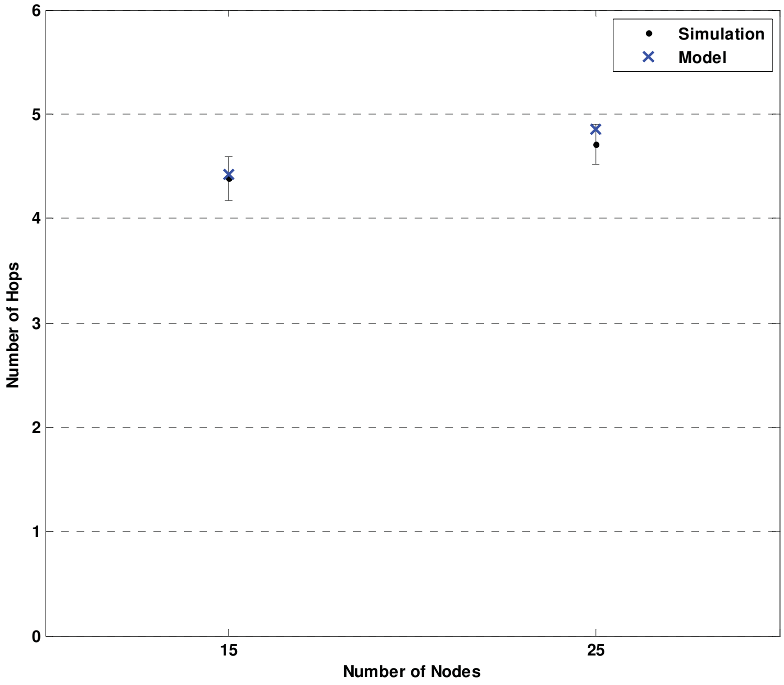

Figure 5-15: Average number of hops to reach the destination from the source versus the number of nodes in the WSNs (50 x 50 m^2).

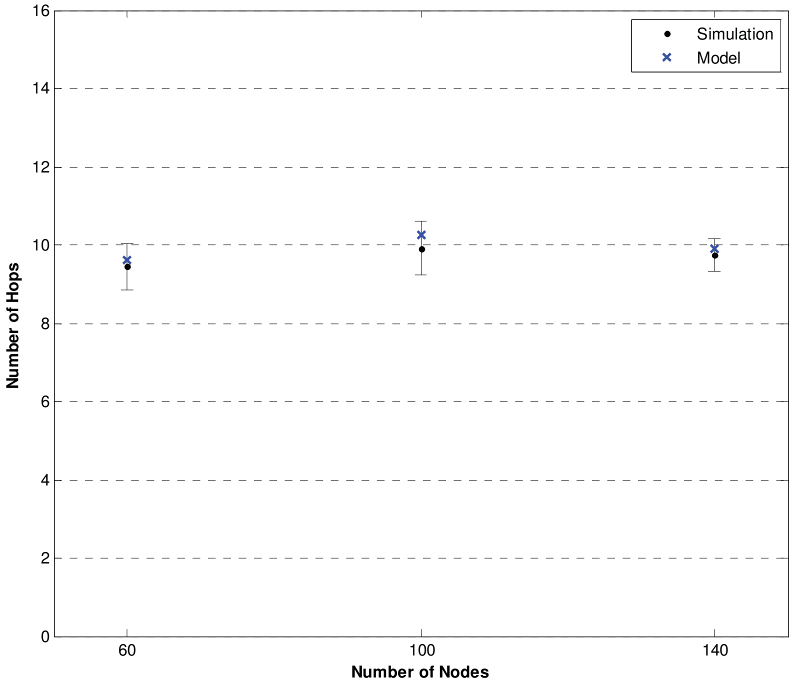

Figure 5-16: Average number of hops to reach the destination from the source versus the number of nodes in the WSNs (100 x 100 m^2).

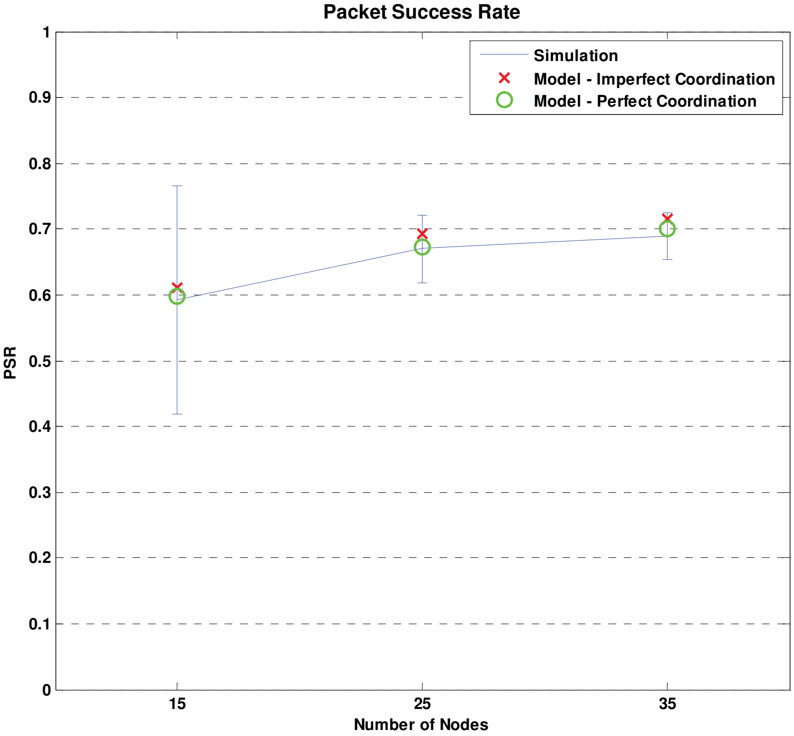

Figure 5-17: Packet Success Rate vs. number of nodes in an area of (50m x 50m). The minimum *Initial_Backoff* time=2.5ms, the minimum *Congestion_Backoff* time = 2.5ms.

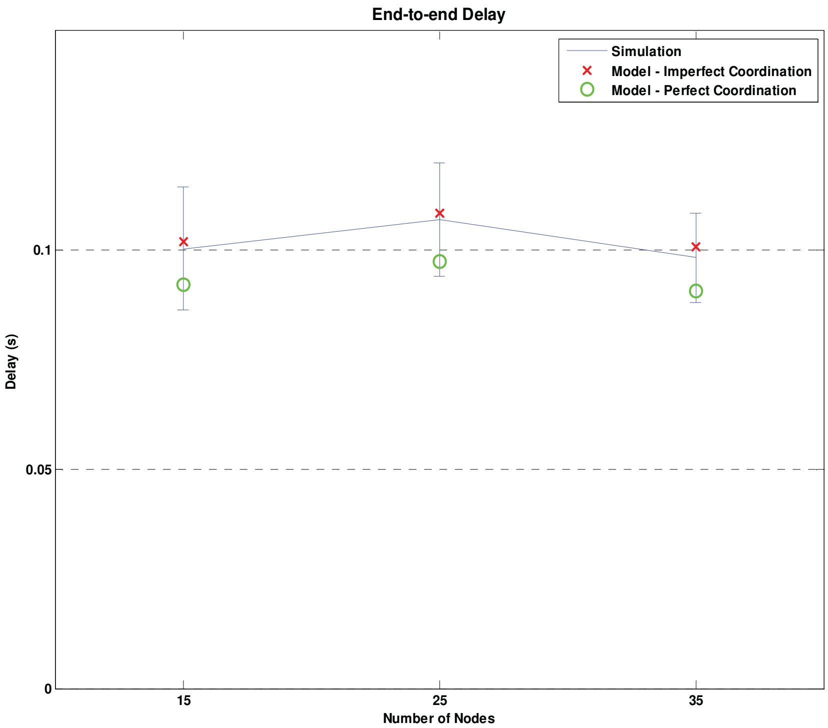

Figure 5-18: End-to-end delay vs. number of nodes in an area of (50m x 50m).The minimum *Initial_Backoff* time=2.5ms, the minimum *Congestion_Backoff* time = 2.5ms.

5.6 Conclusions

In this chapter, we presented an analytical framework of OR that we have proposed with the objective of computing the performance of WSNs that use the OR protocol. To ensure that our framework is realistic, we considered important factors such as the characteristics of a lossy radio channel and CSMA/CA MAC of WSNs. In terms of modelling the typical operation of OR, the proposed framework differs from previous works, especially in terms of modelling the coordination procedure by taking into account issues such as coordination failure and cross-over effects in a randomly deployed WSN. Finally, the correctness of the analytical framework was validated through the use of a WSN simulator.

Chapter 6

An Adaptive Coordination Scheme for the Opportunistic Routing Protocol – A Quality of Service Perspective

Over the years, with the advancement of sensor nodes, a demand to include a quality of service (QoS) requirement has emerged. Since WSNs are always associated with resource constraints especially in terms of power resources, the problem of energy-efficient routing has been an important objective in WSNs. There are many protocols that have been proposed in the literature that incorporate QoS requirements in their definition and implementation. These include SPEED[128], MMSPEED[129], MCMP[80] and ECMP[130]. In general, these protocols rely on utilizing multiple paths between the source and sink nodes. Requirements vary according to their applications such as real-time, reliability, accuracy, energy efficiency, etc. In this chapter, we shall investigate the impact of applying an adaptive coordination scheme to OR using its basic operation. Whereby 'basic' operation means that the reliability performance of OR is purely dependent upon the availability of multiple relay nodes that are without a retransmission mechanism in place. In principle, we are exploiting the spatial diversity properties of WSN to ensure that the reliability requirement can be met. Retransmission is a simple and effective method to increase network reliability. However, it can result in undesirable delays as well as a waste of energy in the WSN environment.

In wireless sensor networks, some data needs to be treated differently when it is being sent to the central sink or base station. For example, it may be a requirement that certain information needs to be reported within a specific time. In this case, any information received after a specific time limit is potentially useless or could cause serious implications due to its late arrival at the central sink node. This type of demand is usually for data associated with emergencies or if there has been an anomaly observed within a monitored environment; this is especially true in a real-time monitoring system.

In terms of incorporating the QoS requirements in a coordination component, to the best of our knowledge, it has never been implemented. Our proposed variant of OR specifically incorporates the QoS requirement during the coordination procedure to further improve the performance of OR especially when dealing with time critical data packets.

In the proposed OR method that was presented in Chapter 4, delays during the coordination stage can incur significant overall delay for a packet to reach its destination. For a high priority node in a CRS with a low packet reception rate, lower priority nodes will be forced to wait until the coordination delay expires before checking and deciding whether to forward or drop the packet depending on whether a higher priority node has successfully received and forwarded the packet. In multi-hop communication, this static coordination procedure will result in a delay that will accumulate over each hop and thus this transmission possibly fails to meet the delay requirements for information reaching the destination. A simple solution to the problem is to change the static coordination order when the PRR of the highest priority relay in the CRS is below a certain threshold value. However, we shall no longer be able to gain the advantage of embracing the opportunism concept which underpins this protocol. In addition, by limiting the CRS to relays that have a higher PRR only, the number of hops will potentially increase and this also leads to longer delays in reaching the destination. This is due to the fact that receiver nodes with a higher PRR have a shorter separation distance between them and the sender. As an alternative, we propose to add an element which exploits the context information that is available from previous and on-going communications. The main idea of utilising this contextual information is to allow the OR protocol to learn the network state and to autonomously adapt to the wireless network dynamicity and, ultimately, to change its operation.

In this chapter, we present an adaptive coordination scheme for OR that is based on a metric that will be known as the Opportunistic Quality Score (OQS) which supports multiple data types flow. Basically, the OQS metric incorporates the probability of successful coordination among relays in the CRS. Through simulation analysis, the performance of the proposed enhancement to OR using this adaptive coordination scheme will be evaluated.

6.1 Problem Formulation and System Model

For WSN applications that need to meet a certain level of QoS such as satisfying a specified delay constraint, reliability standard or a node's lifetime, the OR protocol can be modified to improve its performance. As mentioned in Chapter 4, in geographic or location based OR, the priority of relay nodes in CRS depends on the distance at which the relay is located from the sender node. Basically, the further the distance, the higher will be their priority. Due to this approach, the priority of a relay node becomes inversely proportional to its link quality. Hence, the end-to-end delays may actually be longer for OR using such a static coordination scheme.

By incorporating a service differentiation mechanism, each node can determine the quality criteria for every data packet that WSN applications need to handle. For example, in our study, a WSN application is assumed to be dealing with two types of data packet that refer to non-time critical (NTC) data (*Msg0*) and time critical (TC) data (*Msg1*). In this study, the exact delay constraint is not specified because it is generally application-dependent. Hence, our goal is to try to reduce the end-to-end delay for packet delivery via an adaptive candidate coordination mechanism with better energy efficiency and packet success rate. Generally, by having an OR version that has a minimum end-to-end delay specification, more real-time WSN application requirements can be satisfied.

In opportunistic routing, we are trying to capitalize on the situation where the possibility of the relay that is located within the end region of the transitional area can still successfully and correctly receive the packet- especially when the *tr* coefficient value is high as mentioned in Section 2.1. In this case, it would be a waste of transmission energy if we ignore it, since this reception will definitely maximize the distance travelled by a packet towards the destination [31]. However, according to [40], the relays that are at the end region of the transitional region have a high probability of achieving low PRR values (i.e. $prr < 10\%$). Hence, if we are just relying on the conventional opportunistic routing procedure, we may get low performance instead. Thus, modification to the implementation of opportunistic routing is required to improve its overall performance.

The basic idea of opportunistic routing is that for every local transmission, a set of forwarding nodes - known as the candidate relay set (CRS) - is chosen and one of them is selected as the actual relay node, based on its reachability at that instant. In practice, a coordination procedure is needed to ensure that a single forwarder is selected based on a decision from among the nodes that have successfully received the transmission. This procedure is also important to avoid collisions and redundancy, since multiple relays may have successfully received the packet from the source or sender. A common approach to make decisions regarding packet forwarding or suppression among the receivers is through a process known as slotted acknowledgement [15, 19, 93] that requires an exchange of acknowledgement packets.

In a time-based coordination scheme, there is a potential performance deficiency that leads to an increase in the end-to-end delay. Basically, fixed priority information is used for transmission scheduling and to determine the coordination delay time required at each node. In a dynamic and lossy wireless network such as in a typical WSN system, this rule may cause unnecessary transmission delays for the lower priority nodes, especially when the higher priority node has failed to receive the packet from the sender. In the case where WSN is deployed for emergency or real-time monitoring applications, the quality of service (QoS) requirement, especially in terms of delay, will be more stringent. Typical delay constraints are usually set in such applications.

6.2 Adaptive Coordination Scheme

With the proposed energy efficient selection metrics for OR designated for wireless sensor networks [14, 18], the quality aspects of the data involved are not a major issue since the transmission is performed in a manner that is similar to a best effort strategy. Basically, the selected candidate relay nodes are determined using the objective of sending the data packet to the destination with the most efficient communication energy utilization. Moreover, previous variants of OR which were based on a fixed time-based slotted coordination scheme maintain the sequence and the coordination waiting time of forwarding the received data towards the destination. The adaptive coordination mechanism for relays in CRS is proposed here with the aim of maintaining the energy-efficient metric of OR and adding context awareness to OR in terms of the opportunistic quality for the candidate relay set to improve the performance of OR with respect to the end-to-end delay. Generally, the OR protocol with the adaptive CRS coordination scheme requires several modifications to the existing protocol implementation.

6.2.1 The Opportunistic Quality Score (OQS)

In this section, a metric score specifically designed for coordination in OR with a quality perspective being taken into account will be presented. The OQS is an online score metric that measures the quality of the relays in opportunistic routing protocol. This score metric is used during the coordination stage between the selected nodes within the CRS region.

Due to the adoption of Implicit Acknowledgement scheme in our version of OR presented in Chapter 4, additional *online* or real-time information regarding quality of the *opportunistic communication* between a node and its CRS node can be inferred - based on the knowledge of previous communications. Furthermore, this process can be performed without the need for the exchange of any additional control packets that would incur overhead communication costs. Instead of determining a new set of CRS nodes that is not energy-efficient, we use an opportunistic quality score (OQS) that can be used to adaptively change the coordination delay time of lower priority nodes when dealing with time critical data packets (*msg1*). Basically, for every packet transmission, through an Implicit Acknowledgement procedure, each node can determine which node within its CRS has successfully received and forwarded the packet.

Let us assume that N^0 and N^1 represent the total number of packets transmitted by node *i* according to a normal coordination or an adaptive coordination scheme respectively. Based on this information, the estimated number of implicit acknowledgement packets ϕ, from every node (j) in CRS of node *i* (ω_i) of size r can be determined based on equation (6.1).

$$\begin{aligned} \phi_j^0 &= p_{i,j}^2 N^0 \prod\nolimits_{k=0}^{j-1} (1-p_k), \quad j \in \omega_i \; j=(1,2,..r) \\ \phi_j^1 &= p_{i,j}^2 N^1 \prod\nolimits_{k=0}^{j-2} (1-p_k), \quad j \in \omega_i \; j=(1,2,..r) \end{aligned} \tag{6.1}$$

where $p_{i,j}$ is the packet reception rate between node *i* and node *j*. Note that the superscript and subscript of ϕ represent the type of coordination scheme and the ID of the relay in the CRS of node *i* respectively. In addition, equation (6.1) also incorporates a product term which represents the probability of failure for the higher priority node to receive the packet. Using this information, the OQS ($\mathbb{Q}$) of each node in the CRS of node *i* can be determined using equation (6.2) where A_j is the total number of implicit acknowledgement packets received from node j.

$$\mathbb{Q}_j^0 = \frac{\min(\phi_j^0, A_j)}{\phi_j^0}, \quad j \in \omega$$
$$\mathbb{Q}_j^1 = \frac{\min(\phi_j^1, A_j)}{\phi_j^1}, \quad j \in \omega \tag{6.2}$$

The minimum function used in the numerator is introduced to handle a situation where $A_j > \phi_j$ could occur, especially when link qualities between relays are low. In this case, there is the possibility that the coordination failure among relays in CRS is high, that can result in multiple implicit acknowledgements. Finally, the total OQS value $(0 \le \overline{\mathbb{Q}} \le 1)$ for each node is determined, based on the following expression:

$$\overline{\mathbb{Q}}_j = \lambda_1 \mathbb{Q}_j^1 + (1-\lambda_1)\mathbb{Q}_j^0 \tag{6.3}$$

where λ_1 is ratio of the packet arrival rate of *Msg1* to *Msg0* data packets at the source node. Basically, the $\overline{\mathbb{Q}}$ value is defined as the quality level of nodes in the CRS that are operating under opportunistic routing. In general, a higher value means the greater the chances of the nodes in the CRS to take part, according to the coordination rules in opportunistic routing. The additional communication overhead to implement this coordination scheme compared to other schemes [14, 15, 18] is the introduction of the OQS flag (RT) in the packet header to indicate the ID of the CRS that has the highest OQS level as depicted in Figure 6-1.

Candidate Relay List	**RT**	**Payload**

Figure 6-1: The simplified frame format for ACOR.

In Figure 6-2, we show an example of how a sender node changes and sets the priority level of its candidate relay nodes. From Figure 6-2, let us assumes that after some time t, it is observed that the product of OQS and the PRR of the highest priority relay (P1) falls below the required threshold (γ) and the product of OQS and the PRR of lower priority relay (P3) is the highest. In this case, whenever node S is dealing with time-critical data packet (*Msg1*), it will update the RT flag in the data packet to the lower priority node with the highest product of OQS and PRR. Note that, we are setting the priority level of relays (P1) and (P3) to be equal in order to ensure that the OR does not ignore the possibility that relay (P1) can still receive packet *Msg1* successfully which represents the maximum advancement progress towards the destination. When this happens, the CSMA/CA mechanism will ensure that the collision can be avoided. In terms of the possibility of packet duplication, the packet duplication detection mechanism can be used to suppress any duplicated packets.

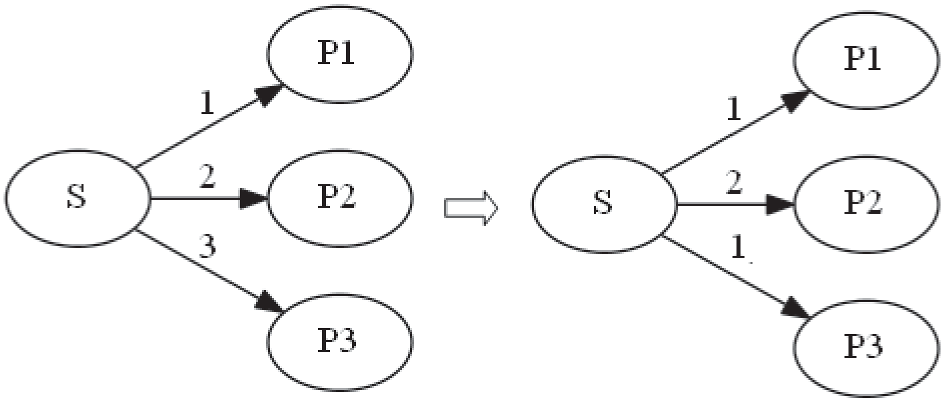

Figure 6-2: Example of priority setting based on $(p \times \overline{\mathbb{Q}})$ and γ values.

6.3 Adaptive Coordination Opportunistic Routing Protocol (ACOR)

The distributed nature of the adaptive coordinated scheme allows relay nodes in the CRS of a node to react quickly to changes in the network and the propagation environment. Based on the $\overline{\mathbb{Q}}$ value and the packet reception rate (p) of each relay in the CRS, for every time critical (*Msg1*) packets, the decision whether to apply the static coordination or the adaptive coordination scheme among the relay nodes in the CRS is based on condition (6.4) where γ is the threshold value.

$$(p_{highest\_priority} \times \overline{\mathbb{Q}}_{highest\_priority}) < \gamma \tag{6.4}$$

If the condition in (6.4) is true, the OQS flag (RT) in the packet header will be assigned with the index of the relay (j) in the CRS that has the maximum product of packet reception rate and OQS value (i.e. $p_j \times \overline{\mathbb{Q}}_j$). The work flow of the OR with an adaptive coordination scheme on the transmitter is shown in Figure 6-3. Based on this setting, when a lower priority relay receives the packet, it will change its coordination delay time ($T_{forward}$) accordingly to increase the chances of delivering the packet faster as highlighted in Figure 6-4. Note that on the receiver, the OQS will only affect the coordination delay of lower priority nodes.

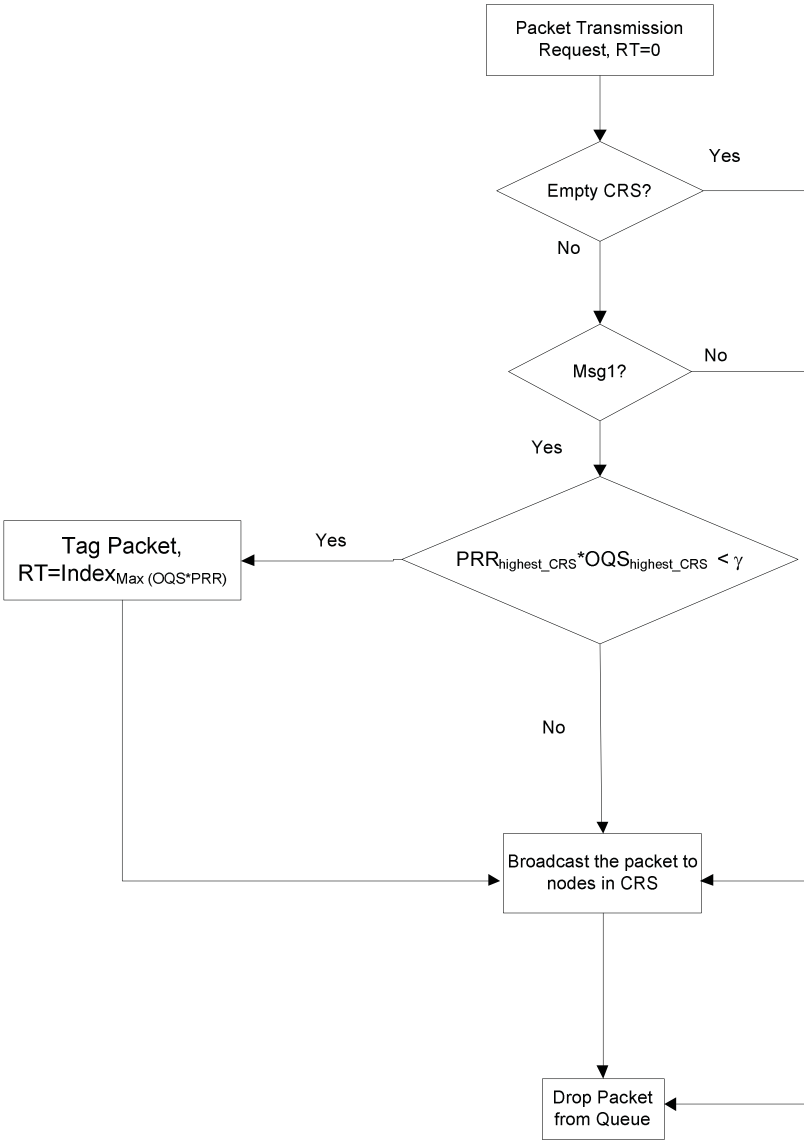

Figure 6-3: The flow chart for OR with adaptive coordination of CRS on a transmitter.

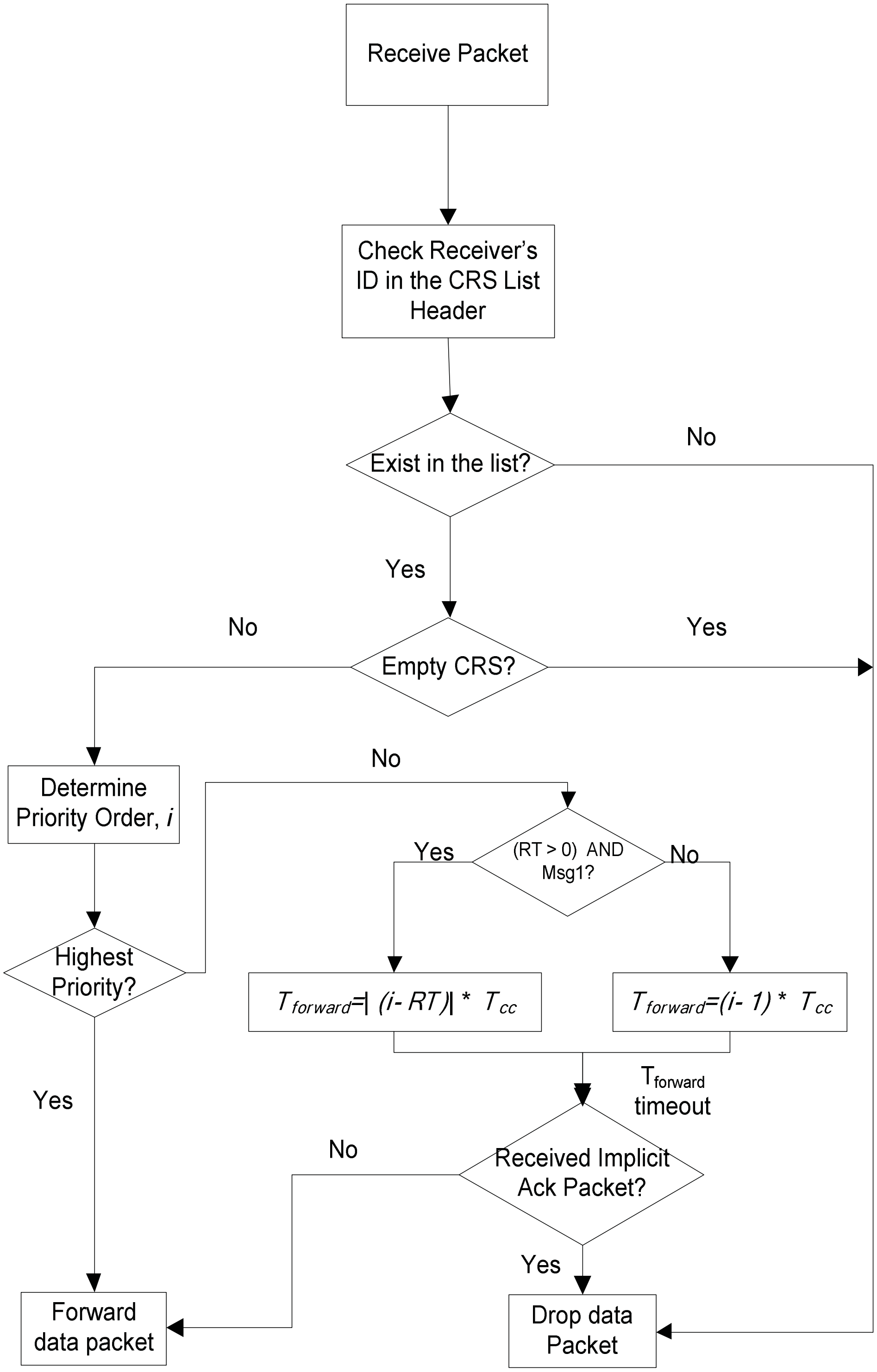

Figure 6-4: Flow chart for OR with Adaptive Coordination of CRS on a receiver where T_{cc} is a coordination coefficient delay constant.

6.3.1 Estimation of OQS

The estimation of an opportunistic quality score is performed using local information collected at each active relay node and in a distributed manner. The distributed manner of estimating the OQS allows the routing decision to react quickly to changes in the network and propagation environments. The periodic updating of the OQS can ensure that the routing decision can promptly react to changes in link probability due to changing wireless conditions, traffic, etc. In our implementation, to reduce the computational and processing time, rather than computing the $\overline{\mathbb{Q}}_j$ for every packet transmission, we estimate the $\overline{\mathbb{Q}}_j^*$ at a fixed time interval (t') by combining the newly measured $\overline{\mathbb{Q}}_j(t)$ value at time *t*, with the previous $\overline{\mathbb{Q}}_j^*(t-t')$ via an exponential weighted moving average (EWMA) using α as the tuning parameter as defined in equation (6.5).

$$\overline{\mathbb{Q}}_i^* = \alpha\mathbb{Q}_i(t) + (1-\alpha)\overline{\mathbb{Q}}_i^*(t-t') \tag{6.5}$$

The tuning parameter α which indicates the weighting associated with current measurements can be set depending on types of WSN applications or the physical environment of the areas that are being monitored. In this study, we assume that the WSN applications are dealing with multiple data types and one of the data types is a time-critical data packet that requires special attention to be delivered to the destination quickly. Hence, in this case, greater emphasis should be given to the latest and current measurements to estimate the OQS value (i.e. $\alpha > 0.5$).

6.4 Performance Evaluation

In this section, we present a simulation analysis to study the performance of OR with the adaptive coordination scheme that we have proposed.

6.4.1 Simulation Setup

The performance of the OR protocol is evaluated through simulation using the simulator Prowler [106] and based on similar assumptions and setup as described in Section 5.5.1. A brief summary of the various simulation parameters used is presented in Table 6-1.

Table 6-1: Simulation parameters.

Parameter	Values
Path loss exponent, γ	3.5
Log-normal shadowing variance, σ	3.8
Receiver Sensitivity	-105 dBm
Transmission Power	6 dBm
Minimum *Initial_Backoff*	50 slots
Data Packet Length	50 Bytes
Coordination Coefficient Delay, T_{cc}	25 ms
OQS Estimation interval	1s
Retransmission Limit	0

We compare the performance of the OR with an adaptive coordination scheme (adaptive CRS) against OR with a static CRS coordination scheme where lower priority nodes do not change the coordination delay time over the whole session of the simulation test. To measure the performance of the schemes with different network densities and topologies, we tested these schemes in 2 sets of network size containing 50 and 100 nodes respectively within a 100 x 100 m^2 square region. For each set we randomly generated 5 different topologies and we ran simulations for 5 runs with different random number seeds for each topology. The source and the sink nodes are fixed at locations (0, 0) and (100, 100) respectively and the traffic was generated at the source node according to an exponential distribution at an average rate of 1 packet per second with no packet retransmission. For every packet generated at the source, the type of the packet (*Msg1* or *Msg0*) for each packet follows a normal distribution with a mean of 0.2 and 0.8 respectively. These values indicate that 80% of the time, the WSN will be dealing with normal data types that involve periodically reporting tasks and 20% of the time it will be dealing with urgent data that requires fast delivery to the destination. In addition, the tuning parameter α, in the EWMA estimator is set to be 0.9 to ensure the estimation gives greater weight to the more recent OQS value - which is appropriate due to dynamicity of wireless network conditions.

The following performance metrics are used to evaluate the performance of the OR protocol with the adaptive coordination scheme:

- *End-to-end delay* – the time delay for a packet from the source to its destination
- *Packet Success Rate* – the total number of packets received at the destination versus the total number of packets sent from the source.
- *Energy efficiency* – the ratio between the numbers of packets received at the destination and the total energy consumption of all the active nodes that take part in communication operations (including unsuccessful transmissions) to send the data along the source-destination path.

6.4.2 Simulation Results and Analysis

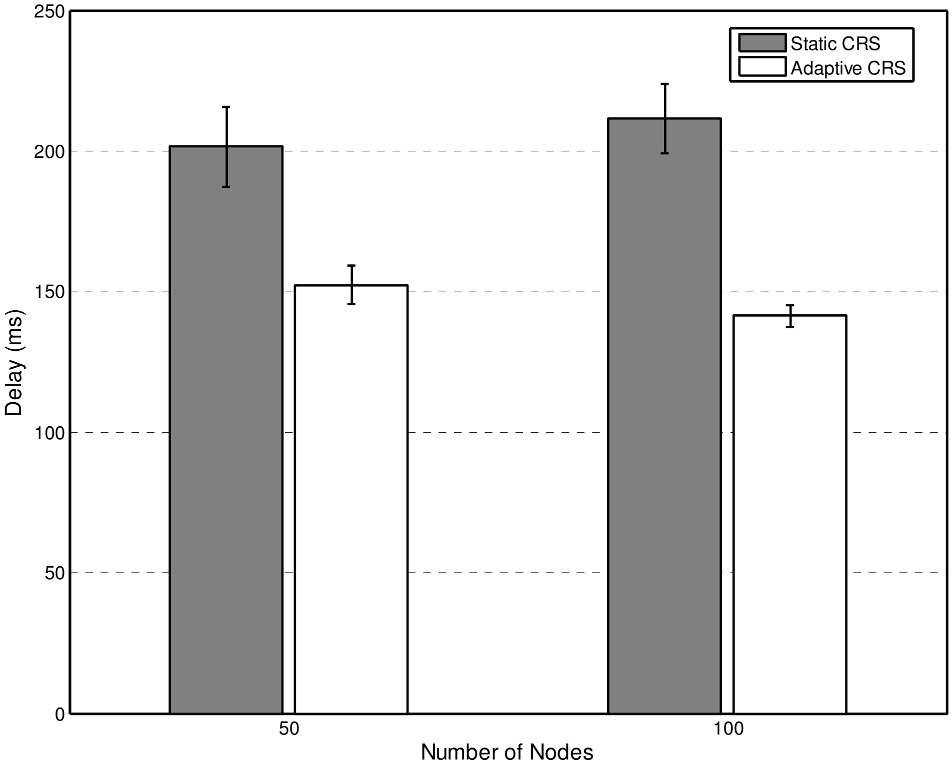

Figure 6-5: End-to-end delay for time-critical data packet (*Msg1*). $\gamma = 0.5$, $\alpha = 0.9$. (Vertical bars show confidence intervals at 95%).

Figure 6-5 shows the performance of OR with the adaptive coordination scheme in terms of end-to-end to delay as compared to OR with the static coordination scheme in WSN networks with different sizes. We can observe that the average end-to-end delay for packet *Msg1* in the OR with the adaptive coordination scheme is lower for both network sizes.

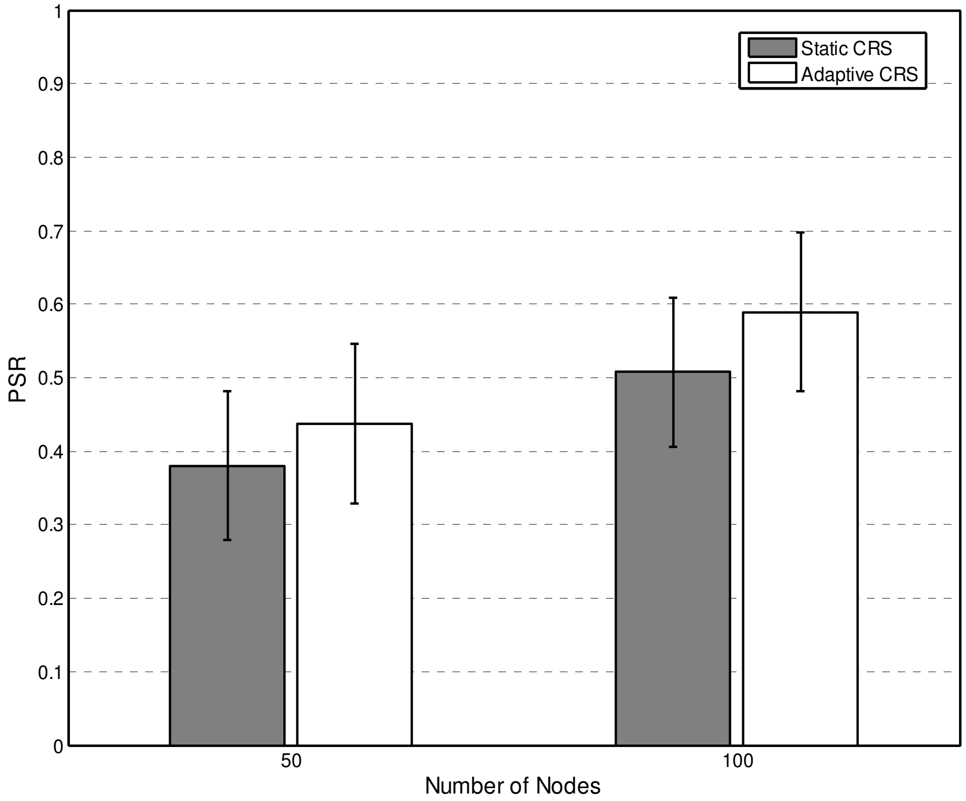

Figure 6-6: Packet success rate for time-critical data packet (*Msg1*). $\gamma = 0.5$ **,** $\alpha = 0.9$ **. (Vertical bars show confidence intervals at 95%).**

Based on a reliability criterion, the performance of OR using the adaptive coordination scheme, we can see that in Figure 6-6, our proposed scheme achieves a higher reliability when compared with normal OR using a static coordination scheme. Hence, for urgent or time critical information (*Msg1*), through our proposed scheme, the chances for the information to be delivered successfully and on time will be higher than the normal OR.

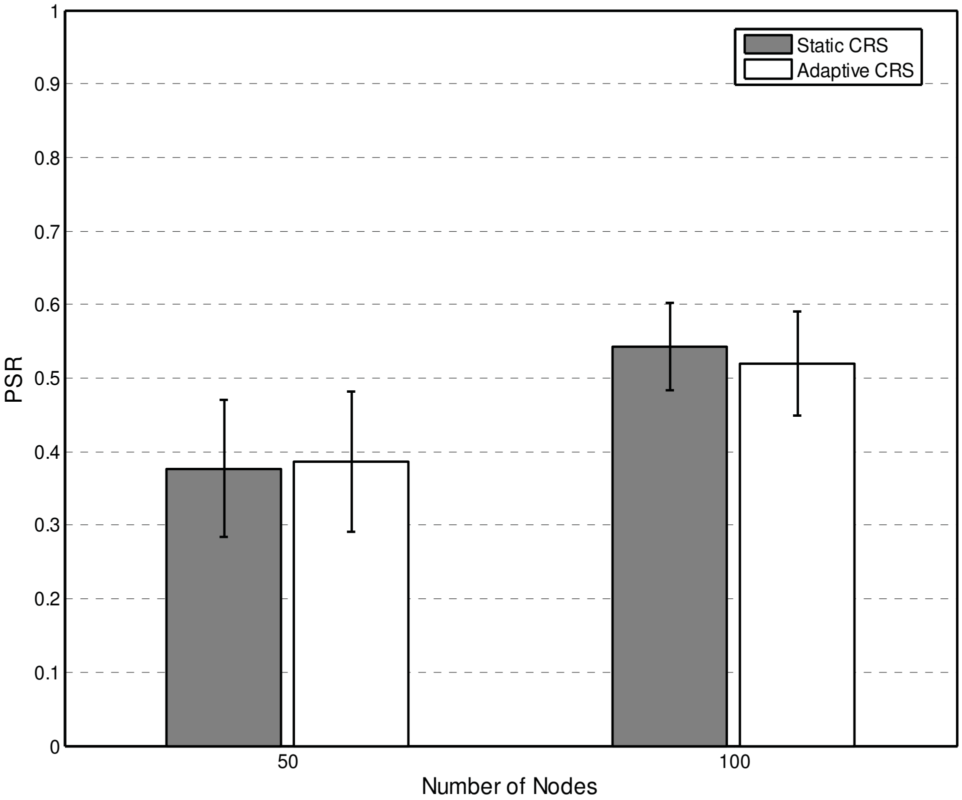

Figure 6-7: Packet success rate for non-time-critical data packet (*Msg0*). $\gamma = 0.5$, $\alpha = 0.9$. **(Vertical bars show confidence intervals at 95%).**

In Figure 6-7, the impact of using OR with an adaptive coordination scheme is shown with regard to the reliability performance of normal data (*Msg0*). As can be seen, the packet success rate of this data type did not get affected significantly. This is expected, since for packets of *Msg0*, the sequence and delay for the coordination operation do not change. It was also observed that in dense networks, there was a slight decrease in the packet success rate for packet type *Msg0* due to the increase of number of packet collisions. For packet type *Msg0*, we assume that, since the data is sent periodically, a slight decrease in the packet success rate is quite negligible. In addition, for any missing information of packet type *Msg0*, the sink can employ prediction techniques on the missing packets such as proposed in [131].

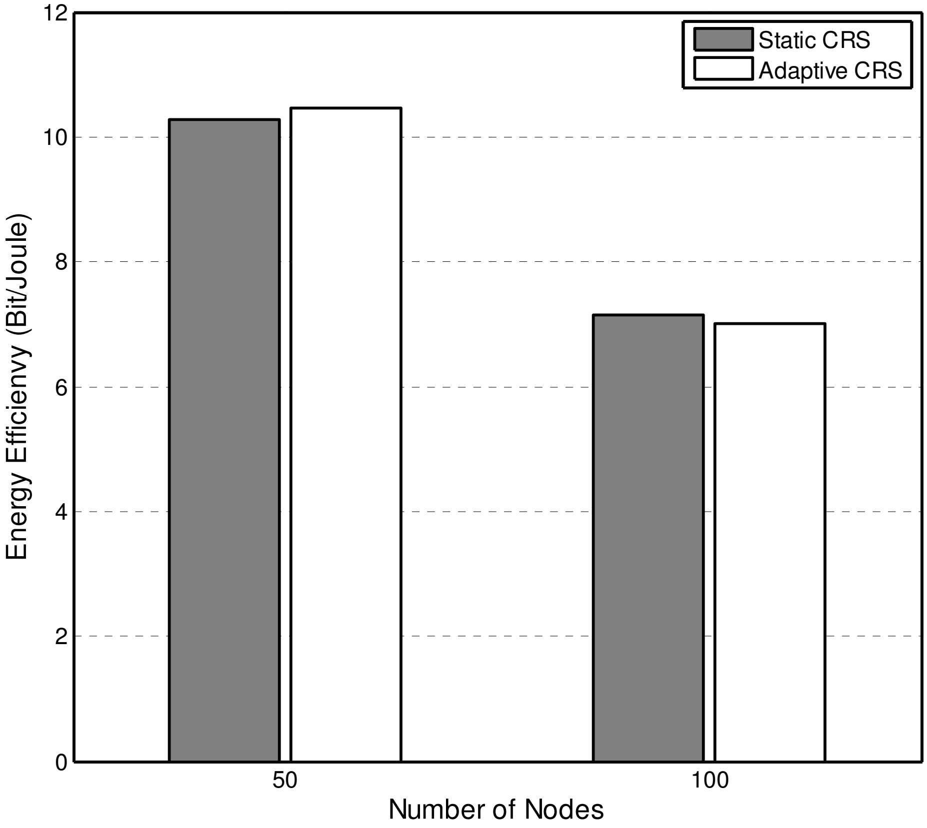

Figure 6-8: Energy Efficiency versus the network size. $\gamma = 0.5, \alpha = 0.9$.

The effect of network density on the overall energy efficiency is illustrated in Figure 6-8. In general, the energy efficiency degrades as the network becomes a denser due to a greater involvement of more nodes and thus it leads to higher energy utilization. Nevertheless, the adaptive scheme manages to achieve a similar efficiency using the normal OR protocol but with a lower end-to-end delay and higher reliability for the urgent data packet.

6.4.3 Sensitivity Analysis

Since the decision to adaptively change the forwarding sequence and coordination time delay depends on the OQS threshold (γ), we also investigate the impact of tuning this value to the performance of adaptive OR dealing with time critical data (*Msg1*). In the simulation analysis, we set the threshold values in the range between 0 and 1. Basically, when the threshold is equal to zero, we are dealing with normal OR in which the relay nodes in the CRS of a particular node will follow a fixed forwarding sequence and waiting time based on its priority. The network topologies and sizes that we used in this evaluation are 50 and 100 nodes with simulation parameter values set according to Table 6-1.

In Figure 6-9, it is shown that the end-to-end delay is lower than normal OR ($\gamma = 0$) as we increase the threshold value up to its maximum value. Basically, the end-to-end delay will be lower when we increase the threshold value since the decision to change the sequence and waiting time is performed more frequently with the stricter threshold value. Note that, for a network size of 50 nodes, the end-to-end delay is monotonically decreasing whereas, for a WSN of size 100 nodes, the minimum end-to-end delay is achieved when the threshold value is set to 0.5. The reason for this effect is due to the increase in network traffic; especially in a denser network. Generally, the higher the threshold, the more frequently the lower priority nodes will update their forwarding sequence and waiting coordination time to ensure the packet is being delivered faster to the destination. Thus, with the increase in network traffic, the number of collisions is also potentially high. Nevertheless, from Figure 6-9, it is shown that our proposed OR with an adaptive coordination scheme performed better than normal OR for all cases in the simulation analysis.

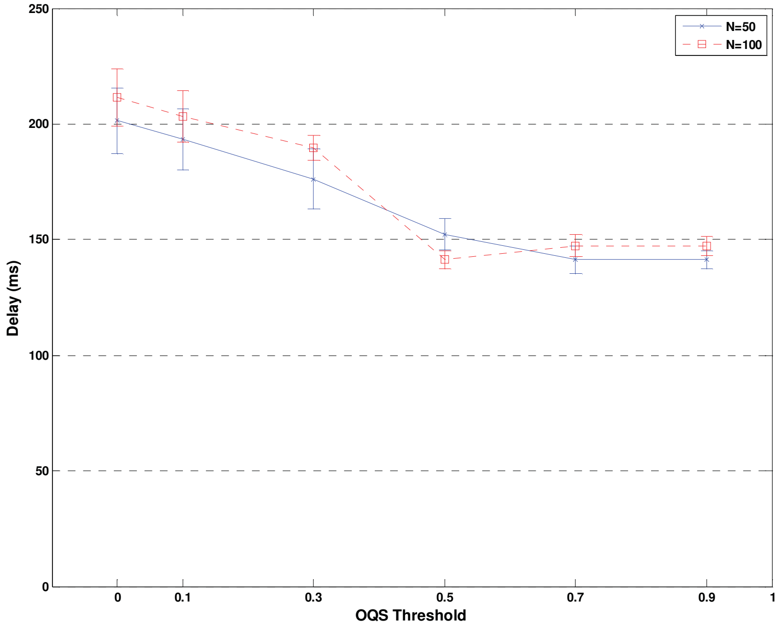

Figure 6-9: The effect of setting the OQS threshold (γ) value to the end-to-end delay of packet *Msg1* of WSNs (Vertical bars show the standard deviation of the simulation analysis).

The effect of tuning the γ value to the reliability performance of the OR with an adaptive coordination scheme and dealing with urgent data packets is illustrated in Figure 6-10. As can be observed, our proposed adaptive OR protocol achieves better performance in terms of packet success rate than normal OR ($\gamma = 0$). In addition, it is also shown that, as the threshold value is increased, the packet success rate also increases. Moreover, similarly to our earlier observations with regard to the density of the network, for the packet success rate, the denser the network, the higher the reliability due to the availability of more relay nodes between the source and destination nodes

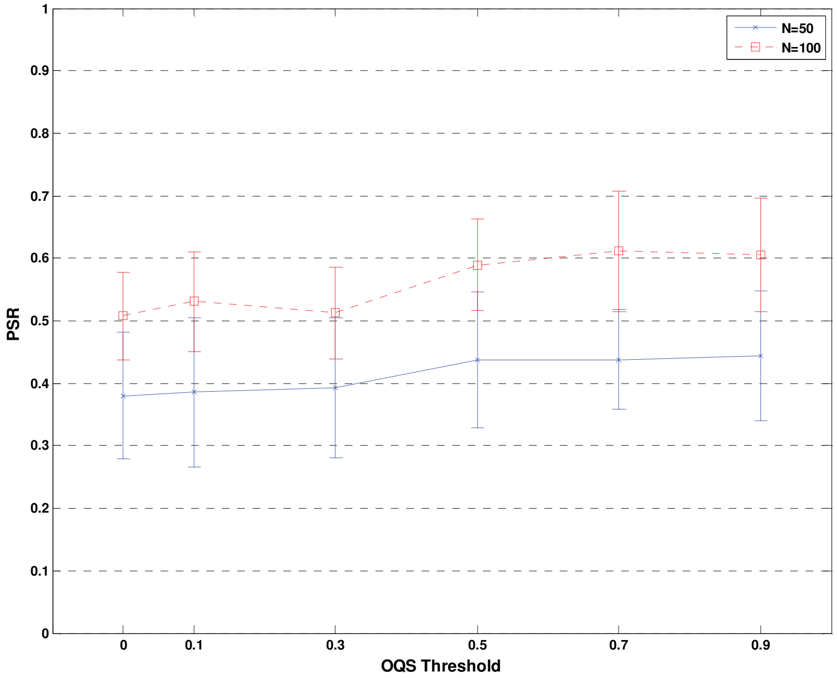

Figure 6-10: The effect of setting the OQS threshold (γ) value to the packet success rate of packet *Msg1* of WSNs

With regards to the energy efficiency performance of OR with the adaptive coordination scheme, Figure 6-11 compares the energy efficiency achieved by our proposed protocol with different threshold values and for different network densities. Since the objective of adopting the proposed adaptive OR is to lower the end-to-end delay experienced by packets of the *Msg1* type, it is clear that is has been successful. The results illustrated in

Figure 6-11 show that the adoption of adaptive OR does not introduce any additional energy efficiency overhead.

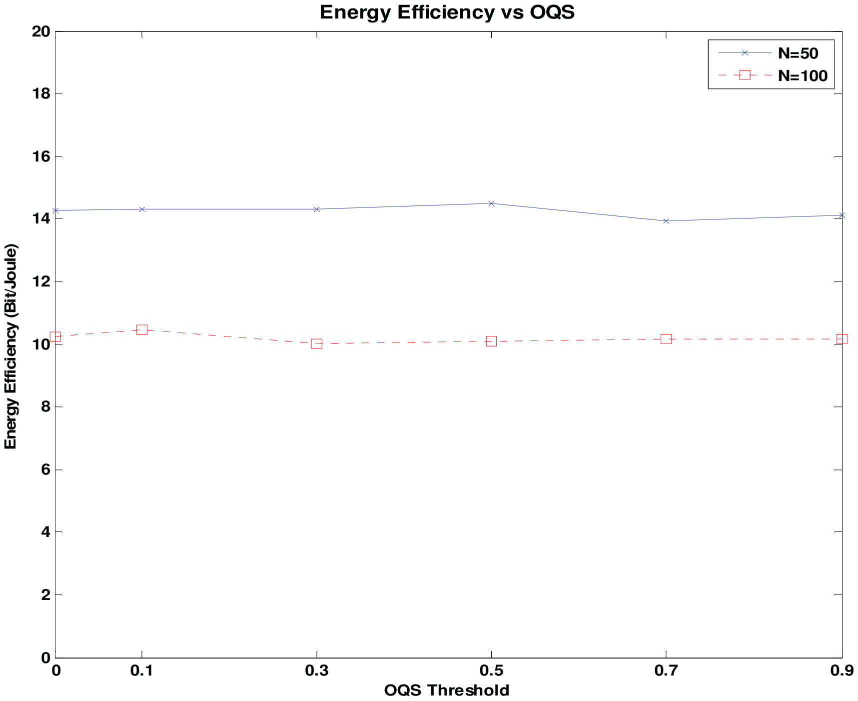

Figure 6-11: The effect of setting the OQS threshold (γ) value to the energy efficiency of WSNs

6.5 Conclusions

In this chapter, we have proposed and analysed an adaptive coordination scheme for OR with the objective of meeting quality of service objectives, especially the end-to-end delay. The coordination operation in the proposed solution is implemented based on the metric that we introduced known as the Opportunistic Quality Score (OQS). The effectiveness of adopting the adaptive coordination scheme of OR in WSN to reduce end-to-end delay was highlighted through a simulation analysis. Overall, by relying on the selection metric that aims to select relays in the CRS with the most efficient communication energy utilization, the proposed adaptive scheme can further improve the overall performance of WSNs using OR.

Chapter 7

An Enhanced Analytical Framework For OR with Quality of Service Support

In this chapter, we shall present an analytical framework for our OR protocol that incorporates the changes that we have proposed - especially with regard to the coordination operation. This framework will be used to model the performance of Adaptive Coordination Opportunistic Routing (ACOR) in terms of reliability and end-to-end delay of time-critical (TC) data.

7.1 Modelling of the adaptive OR protocol

Based on the absorbing Markov Chain (MC) model introduced in Section 5.3 which was used to model OR with a static CRS coordination scheme, we now propose a modification to the analytical framework model that incorporates the adaptive nature of the coordination scheme to model the performance of ACOR in terms of end-to-end delay. By referring to the flow chart for OR with our adaptive coordination scheme in Figure 6-3 and Figure 6-4, we can observe that the conventional sequence of OR will not be followed when the product of OQS and link quality of higher priority nodes falls below a certain threshold value. In particular, the sequence and the delay during the coordination procedure will be updated depending on the current level of the OQS metric defined by equations (6.2) and (6.3).

7.1.1 ACOR Absorbing Markov Chain

We now develop a modified absorbing Markov Chain (MC) that includes the changes to the sequence of coordination and delay in our adaptive coordination scheme. In this model, the transitional probabilities between each nodes and its relay in the CRS are derived and represented as D_{oqs} by incorporating the effect of using the OQS value.

In general, the transitional probability between a node and its CRS for OR with our adaptive coordination scheme differs from OR using the static coordination scheme. By estimating the OQS for each relay in the CRS, when the product of OQS and link quality value of the highest priority relay is below a certain threshold value, the probability of the lower priority relay being selected as the next forwarder will change. In addition, its coordination delay is also affected which will intuitively result in a faster packet forwarding time. In terms of the coordination delay ($T_{forward}$) of such a relay, in the implementation of OR with adaptive coordination scheme, the coordination delay of the relay with the maximum product of OQS and link quality value will be updated to zero which will be the same as the highest priority node to forward the message in the next hop. Hence, in a situation where the highest priority node also successfully received the packet and tries to forward it, no coordination operation will take place since, in general, two relays will attempt to forward it at the same time. However, with the packet duplication mechanism that is assumed to be implemented in all nodes to suppress duplicated packets, this effect will be minimised. With this new arrangement, the transitional probability of the lower priority relay with the highest product of OQS and link quality can ignore the coordination factor in its calculation.

With the same assumption being made regarding the network, channel and MAC models as described in Section 5.1, by letting the number of packets sent to be normalised to 1, the mean OQS of every relay (j) in the CRS (ω_i) of size r for a particular node (i) can be estimated based on the following expression:

$$\overline{\mathbb{Q}}_j = p_{i,j}^2 \prod_{k=1}^{j-1} (1 - p_{i,k}), \quad j \in \omega_i, j = (1, 2, .., r) \tag{7.1}$$

where $p_{i,j}$ is the packet reception rate between node i and node j. Equation (7.1) incorporates the product terms of unsuccessful transmission probabilities of higher priority nodes to receive the packet correctly. In addition, for every node i with a set of ordered candidate relays of size m, a destination node (n), unsuccessful state ($n+1$), dead-end nodes (a) and the assumption of independent delivery probabilities between nodes, the transitional probabilities of matrix D_{oqs} are given by:

$$d_{s_i,s_j} = p_{i,j}$$

$$j = \begin{cases} c_i(1) \\ c_i(O^*) : O^* = \text{ the ID of the relay in CRS with maximum } (p \times \overline{\mathbb{Q}}) \text{ value} \end{cases} \tag{7.2}$$

$$d_{s_i,s_j} = p_{i,j} \times q_j(l), \qquad j = c_i(l),\ l = \{3,..,m\} \tag{7.3}$$

$$q_j(l) = \min\left(1, \left(\prod_{k=1}^{l-1}\left(1 - p_{i,c_i(k)}\right) + \prod_{r=1}^{l-1}\left(1 - p_{c_i(r),j}\right)\right)\right) \tag{7.4}$$

$$d_{s_i,s_{n+1}} = \prod_{k=1}^{|c_i|}\left(1 - p_{i,c_i(k)}\right), i = 1,2,..,n-1 \tag{7.5}$$

$$d_{s_n,s_n} = 1, \qquad d_{s_{n+1},s_{n+1}} = 1 \qquad d_{s_a,s_a} = 1 \tag{7.6}$$

Equation (7.2) is the probability that the highest priority node and the relay with the maximum value of the product of OQS ($\mathbb{Q}$) and packet reception rate (p) will get selected as the packet forwarder. Equation (7.3) gives the probability of a lower priority node being selected as a result of unsuccessful transmission to the higher priority node and the node with the maximum OQS. In addition, the coordination failure among relays in i 's CRS is also taken into consideration to calculate the transition probabilities to those relays as shown in equation (7.4). The *minimum* function in (7.4) is required in order to ensure a valid probability distribution. To account for the total communication failure with all of i 's candidate relays, we define this transitional probability as (7.5). Finally, the three expressions in (7.6) denote the absorbing states of the destination node, failure states and dead-end nodes respectively.

Again, based on the theory of Markov Chains with absorbing states [76], we define the fundamental matrix as $F_{oqs} = \left(I - D_{oqs}^{(n-1-|A|)\times(n-1-|A|)}\right)^{-1}$, where the entry $f_{i,v} \in F_{oqs}, (i,v = 1,2,...,n-1-|A|)$ represents the expected number of times the node v is visited for routing the traffic flow from node i to the absorbing nodes and A is a set of dead-end nodes. To derive the fundamental matrix, D_{oqs} is set to be in its *Canonical form* as in (7.7), where I is the $(|A|+2)\times(|A|+2)$ identity matrix, Q is an

$(n-1-|A|)\times(n-1-|A|)$ matrix for all transient states corresponding to nodes in a WSN and R is an $(n-1-|A|)\times(|A|+2)$ matrix for the absorbing states.

$$D_{oqs} = \begin{pmatrix} Q & \mathrm{R} \\ 0 & I \end{pmatrix} \tag{7.7}$$

Finally, based on equations (7.2) - (7.7), we can determine the packet success rate (PSR) for the routing of traffic flow from node i to the destination node n as follows:

$$PSR_{i,n} = \sum_{j=1}^{n-1-|A|} f_{i,j} r_{j,n}, \quad r \in \mathrm{R} \quad f \in F \tag{7.8}$$

7.1.2 Queueing Model

In order to model the end-to-end delay for OR with our adaptive coordination scheme, a similar approach to that described in Section 5.3.2 is adopted. The main aim here is to determine the total sojourn time each packet will spend at the nodes in WSNs which includes the average service time and average waiting time in queue according to equation (7.9).

$$T_i = \overline{X_i} + T_{q_i} \tag{7.9}$$

From equation (7.10) which is derived to estimate the average service time ($\overline{X_i}$) of node i, the component that change significantly in this version of OR is the coordination delay expressed as ($\overline{CO_i}$). This is mainly due to the effect of updating the coordination delay ($T_{forward}$) based on the OQS metric.

$$\overline{X_i} = T_{pkt} + \overline{B} + \overline{CO_i} \tag{7.10}$$

In principle, to estimate the mean coordination delay of relay i , we use the transitional probabilities between nodes in the network that select node i as their relay in CRS derived in D_{oqs} and its mean packet arrival rate, λ_i. Furthermore, the updated coordination delay of node i which is based on its OQS and link quality with respect to all nodes that select node i as the candidate relay in their CRS is represented as vector $\underline{\Omega}_i$. With this information, we can then calculate the mean coordination delay which takes into account the cross-over effect (see Figure 5-6) in a randomly deployed WSN according to equation (7.11).

$$\overline{CO}_i = \sum_{l=1}^{|p_i|} \underline{p}_i(l)\underline{\lambda}_i(l)\underline{\Omega}_i(l) \tag{7.11}$$

where $\underline{p}_i$ is the vector of probabilities of node i being selected as the next forwarder if it received a packet from nodes that have selected the node i as their candidate relays and $\underline{\lambda}_i$ is the vector of packet arrival rates from downstream relays.

Once the average service time for node i has been determined, based on Little's law, the mean waiting time (T_{q_i}) in a queue of size K can be computed using equation (5.43), (5.44) and (5.45). Finally, the mean end-to-end delay between node i and n can be calculated using the following expression:

$$E\left[Delay_{i,n}\right] = \frac{\underline{T}_i}{(1-d^{1}_{s_i,s_{n+1}})} + \sum_{h=1}^{C} \frac{\sum_{j=1}^{n} d^{(h)}_{s_i,s_j}\underline{T}_j}{(1-d^{(h+1)}_{s_i,s_{n+1}})} + \sum_{h=C+1}^{H}\sum_{j=1}^{n} d^{(h)}_{s_i,s_j}\underline{T}_j \tag{7.12}$$

where $\underline{T}$ is a column vector of expected sojourn times for all nodes in the network, C is the limit of the hop count determined when the cumulative probability of the hop count is zero (i.e. $F(h \le C)_{i,n} = 0$) and H is the limit of the hop count determined when the cumulative probability of the hop count is one (i.e. $F(h \le H)_{i,n} = 1$).

7.2 Numerical Results

We now present numerical results for two different sets of WSNs with 50 and 100 nodes that are randomly deployed in an area of size 100 x 100 m^2 from our analytical framework for OR with our adaptive coordination scheme and compare them with simulation results to validate our proposed framework. For the simulation analysis, the setup is based on similar settings that have been described previously in Section 6.4.1. The performance metrics that we are investigating by using the analytical framework and the simulator are packet success rate and end-to-end delay for ad-hoc WSNs.

In Figure 7-1, the reliability performance of WSNs for 50 randomly deployed nodes with adaptive OR using different (γ) values is presented. It is shown that the results derived with our analytical framework are within the 95% confidence limit for all cases. Hence, these results validate the correctness of our framework in terms of modelling the reliability performance of WSN using our adaptive OR.

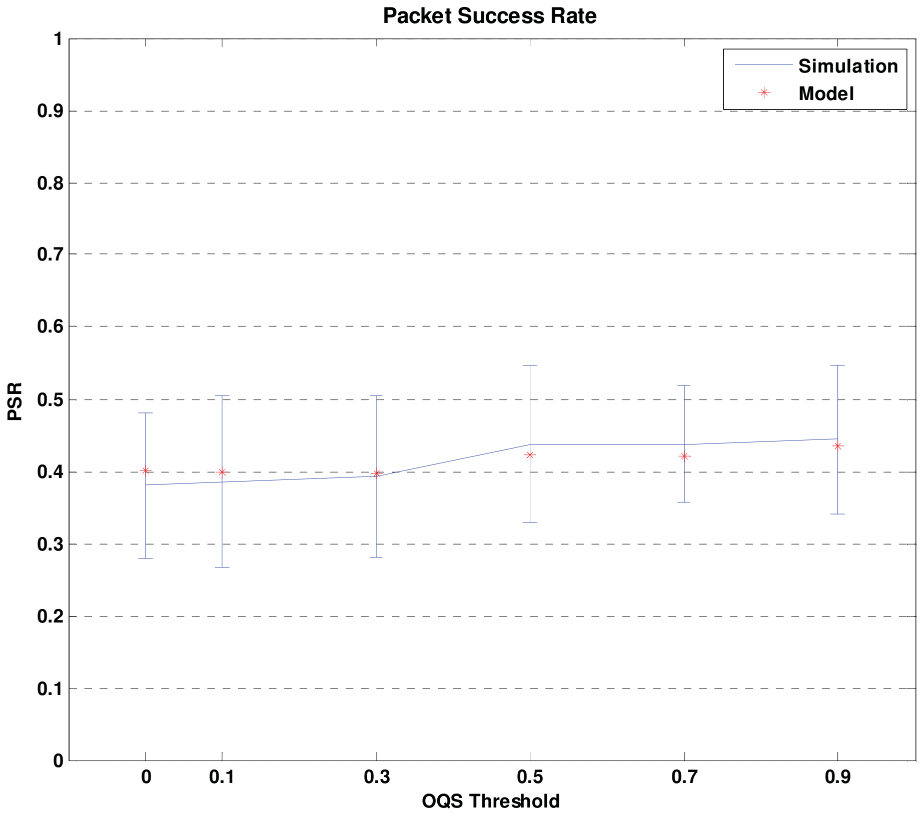

Figure 7-1: Packet Success Rate versus OQS threshold. Number of nodes = 50. Vertical bar represents 95% confidence limit of simulation results.

In terms of end-to-end delay, from Figure 7-2 we can observe that the results predicted by using the analytical framework follow a general and similar trend to the simulation results as the (γ) value is increased. In addition, all of the end-to-end delays being modelled are within the 95% confidence limits, and this suggests that our proposed framework is valid.

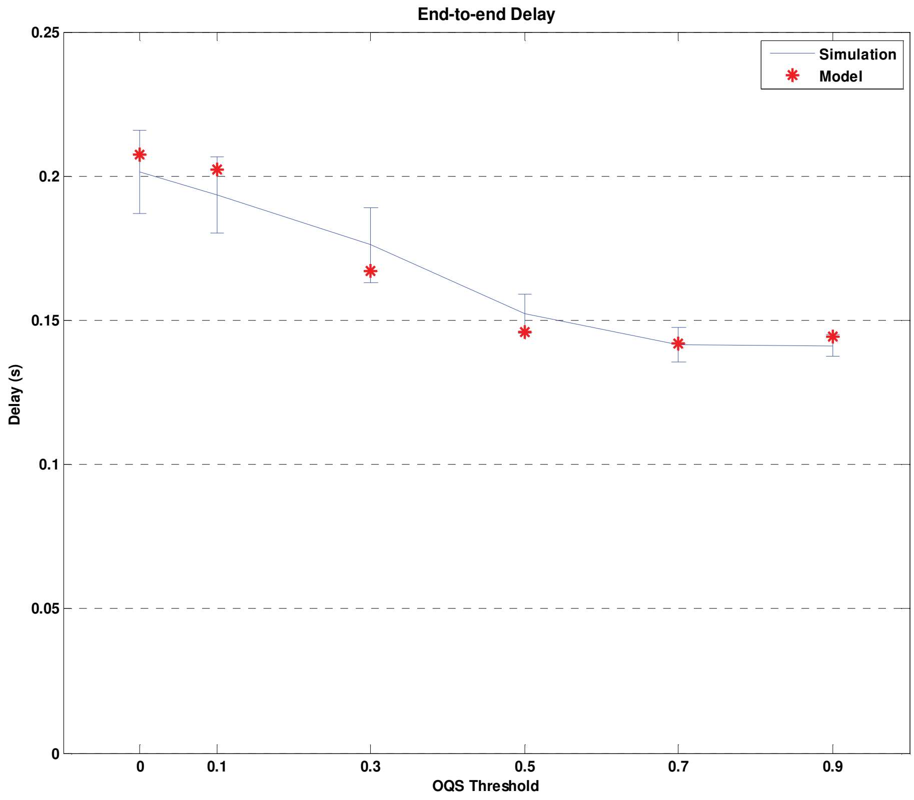

Figure 7-2: End-to-end delay versus OQS threshold. Number of nodes = 50. Vertical bar represents 95% confidence limit of simulation results.

Figure 7-3 compares reliability results of our adaptive OR scheme for 100 nodes determined from our analytical and simulation analysis. As can be seen, for all ranges of the OQS threshold values, the packet success rates modelled using the proposed analytical framework are within the 95% confidence limits of the simulation results and thus, validates the analytical framework.

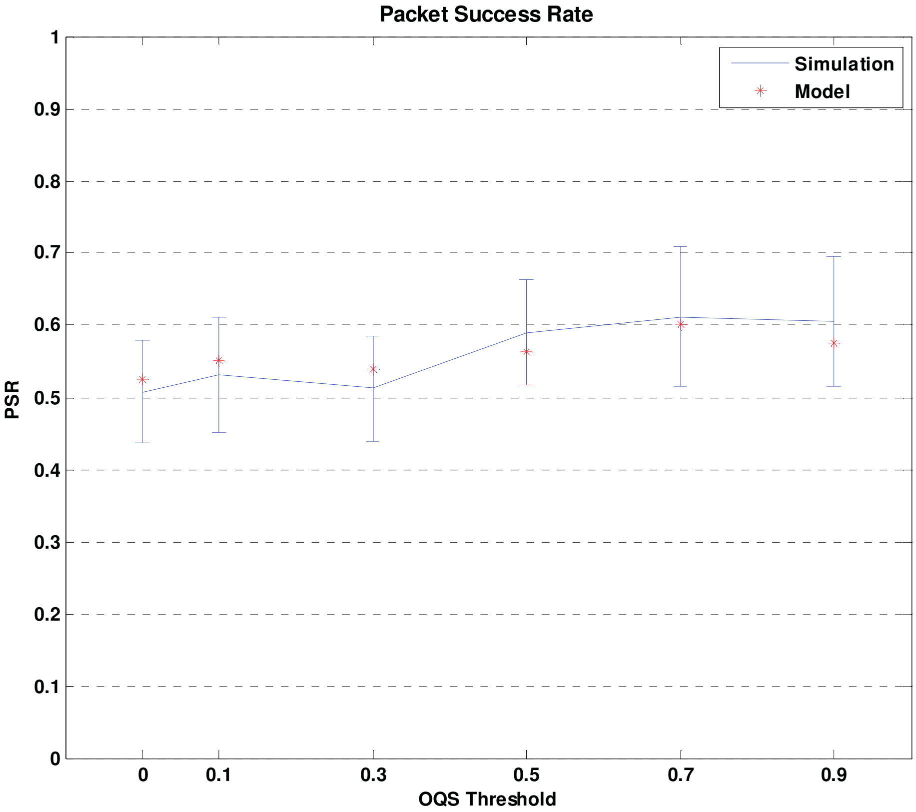

Figure 7-3: Packet Success Rate delay versus OQS threshold. Number of nodes = 100. Vertical bar represents 95% confidence limit of simulation results.

Next, we validate the accuracy of the proposed analytical framework in terms of end-to-end delay for our adaptive OR scheme using 100 nodes. Our results are shown in Figure 7-4. Again, we can see that the end-to-end delay, modelled via the framework match closely with the ones observed in the simulator and they are all within the 95% confidence limits.

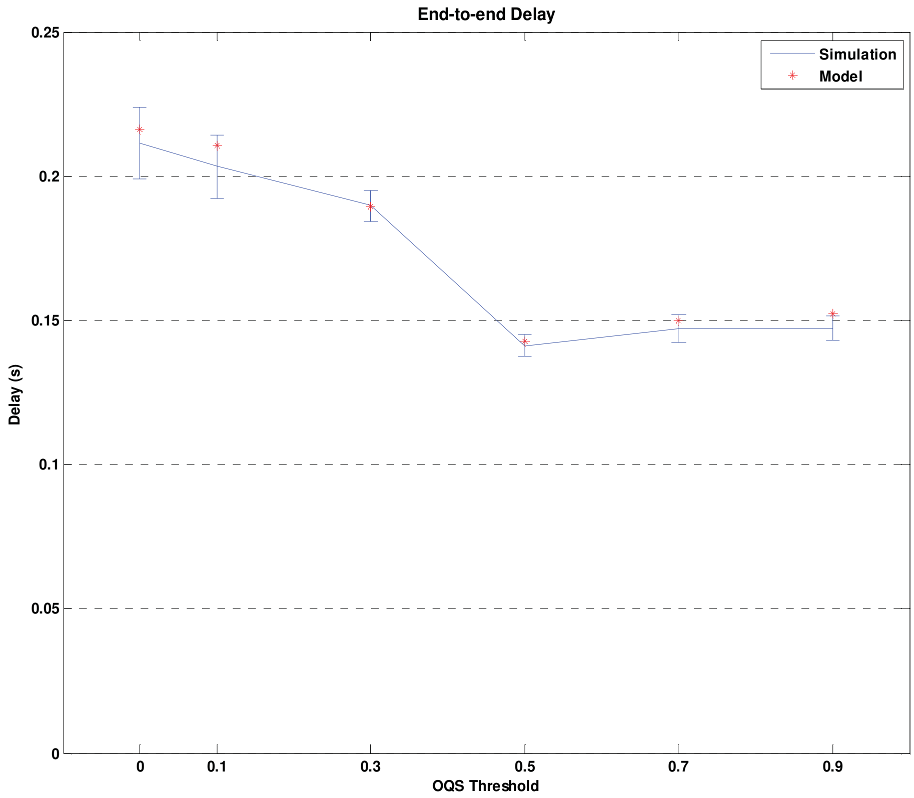

Figure 7-4: End-to-end delay versus OQS threshold. Number of nodes = 100. Vertical bar represents 95% confidence limit of simulation results.

7.3 Conclusions

In this chapter, we set out to evaluate the performance of OR using our adaptive coordination scheme using an analytical model. We proposed an analytical framework which has allowed us to model the end-to-end delay each time-critical packet will experience in the network in order to reach the destination when using the OR with the proposed adaptive coordination scheme. Moreover, the analytical framework can also be used to measure the estimated packet success rate in such WSNs. Finally, we validated the framework through a simulation analysis that validates the accuracy of the analytical framework.

Chapter 8

Conclusions and Future Work

8.1 Summary

The main theme of this research has been to investigate the concept of opportunistic routing in a WSN environment. Moreover, the issue of quality of service has been considered as an integral part of the studies that we have undertaken in this research.

Based on the overview of communication components of a typical WSN and the review of the opportunistic routing protocol undertaken in Chapter 2 and Chapter 3 respectively, we have proposed a variant of OR that is suitable for applications involving WSNs as described in Chapter 4. Based on our goal to reduce the total energy utilisation with respect to the number of transmissions involved in a WSN using OR, we have proposed a coordination scheme known as Implicit Acknowledgement.

Due to the adoption of cross layer concepts in the implementation and design of OR, we have investigated the impact of two main parameters, namely the initial back-off of the CSMA/CA MAC and the coordination coefficient delay of OR using priority-based slotted acknowledgements. We have summarised the importance of setting these parameters to ensure that OR can achieve high performance in a WSN environment. In general, there exist trade-offs in terms performance objectives involving WSNs using OR. This information will be beneficial when setting these parameters for specific WSN applications.

Furthermore, we compared our variant of OR using Implicit Acknowledgement coordination scheme against OR that relies upon explicit ACK control packets for coordination. Based on our simulation results, the benefit of this approach for WSNs in terms of energy efficiency has been shown. Additional advantages of this scheme in terms of end-to-end delay and reliability were also observed in our simulation studies. We further proposed an enhancement to the variant of OR to meet quality of service requirements in terms of reliability. Through the concept of 'soft-QoS', we designed a probabilistic retransmission scheme to be used in our OR with Implicit Acknowledgement coordination scheme. Simulation results also showed that the proposed scheme achieved higher than the traditional retransmission mechanism in terms of energy efficiency and able to meet the provisional reliability requirements.

In Chapter 5, we presented an analytical framework for the OR protocol in WSNs. We adopted Markov Chain and standard queueing theories in the framework to model the performance in terms of reliability and end-to-end delay for WSNs that use the OR protocol. The proposed framework takes into account the physical component of the radio channel, CSMA/CA MAC channel and OR protocol operations in WSNs. Contrary to previous works, issues related to communication failure at the MAC layer such as collision and interference were considered in our framework. Moreover, the effect of coordination failure due to disjointed CRS and cross-over traffic were also taken into account when deriving the analytical framework. We validated the framework by comparing the results derived using the framework with simulation under different settings such as different network sizes and topologies as well as different minimum *Initial_backoff* settings for the MAC layer.

Taking into account the aspect of quality of service, in Chapter 6, we proposed and analysed an adaptive coordination scheme for OR with the objective of meeting the quality of service requirement especially the end-to-end delay in WSNs that handle multiple data types. The proposed scheme was implemented based on the metric that we formulated known as the Opportunistic Quality Score (OQS). We showed the effectiveness of adopting the adaptive coordination scheme of OR in WSNs to reduce the end-to-end delay by simulation analysis. Furthermore, an enhanced analytical framework for the variant of OR with adaptive coordination scheme was proposed in Chapter 7. Once again the validation of the proposed analytical framework was conducted using simulation tools. It was shown that the analytical framework can model the performance of WSNs using OR accurately.

8.2 Future Work

The performance analysis of the proposed variant of OR was mainly based on simulations. Thus, an experimental analysis should be conducted in order to evaluate its effectiveness in real environments of WSNs.

In this study, due to the overheads involved in the duty cycle mechanism that can affect the performance of WSNs in terms of delay and reliability, the mechanism was not considered. Nevertheless, the benefit of extending the lifetime of WSNs through duty cycles is very appealing. Thus, an investigation on how to integrate this mechanism while minimising the end-to-end delay and improving the reliability, should be part of future studies. Basically, through a trade-off analysis, a new variant of OR that incorporates a duty cycle in its selection and coordination operation could be proposed.

The analytical framework that has been proposed in this research is based on several assumptions on the network model for WSNs. In particular, the packet arrival and service rate distribution were assumed to be following homogenous Poisson and Exponential distribution respectively. Studies to determine different and exact distributions of packet arrival and service rates in specific WSN applications should be conducted in order to enhance and generalise the framework.

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APPENDIX: Publications

The publications made from this research are:

1) M. E. Rusli and R. Harris, "An Adaptive Coordination Scheme for Opportunistic Routing Protocol in Wireless Sensor Networks", Australasian Telecommunication Networks and Applications Conference (ATNAC), Auckland, NZ, October, 2010.
2) M. E. Rusli, R. Harris and A. Punchihewa, "Markov Chain-Based Analytical Model of Opportunistic Routing Protocol for Wireless Sensor Networks", IEEE Region 10 Conference TENCON, Fukuoka, Japan, November, 2010.
3) M. E. Rusli, R. Harris and A. Punchihewa, "Quality Aware Opportunistic Routing Protocol with Adaptive Coordination Scheme for Wireless Sensor Networks", International Conference on Computational Intelligence, Modelling and Simulation (CIMSIM), Pahang, Malaysia, September, 2012.
4) M. E. Rusli, R. Harris and A. Punchihewa, "Performance Analysis of Implicit Acknowledgement Coordination Scheme for Opportunistic Routing in Wireless Sensor Networks", International Symposium on Telecommunication Technologies (ISTT), Kuala Lumpur, Malaysia, November, 2012.
5) M. E. Rusli, R. Harris and A. Punchihewa, "An Analytical Framework of Opportunistic Routing Protocol in Time-Critical Applications of Wireless Sensor Networks", Journal of Networks and Computer Applications, *under review,* 2012.