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Transmit power control protocol for multi-path wireless sensor networks

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ABSTRACT

In the recent years, we observed a rapid growing of Wireless Sensor Networks (WSNs) for research and commercial uses. Low-cost/low-power WSNs are utilised in various applications such as smart-home, industrial control, health care, agricultural fields, environmental purposes, biomedical systems, and scientific applications. The aim of this thesis is to develop a novel transmit power control protocol for multi-path non-uniform density single-channel WSNs. The developed protocol has two main purposes: (1) to reduce energy depletion and prolong the battery lifetime of sensor nodes by using transmit power control and, (2) to keep throughput and packet loss neutral by using multi-path routing. A limitation of most previous studies that minimise transmit power is that they fail to take into consideration the throughput reduction. Through a number of case studies, it was determined that trying to reduce the power by using multi-hopping also results in the reduction of end-to-end throughput. Hence, we propose using a multi-path routing protocol to maintain throughput. In this work, given our assumptions, we determined that the optimal number of hops must be between two and eight hops to save energy and the optimal number of paths is two paths to maintain throughput when the transmission rate is high. This is mainly due to the overhead of each packet as we as the receive power of the sensor nodes. It was also determined that there is no need to have more than 2 paths between source and destination in order to achieve throughout neutrality. QualNet 5.1 platform was used to develop “TPC for High Density WSNs” protocol that combines both TPC and some features of the Multi-Path Optimised Link State Routing (MP-OLSR) protocols. The simulation results showed that using two, three, four and five hops scenarios can noticeably enhance the energy efficiency, and the optimal number of non-interfered paths must be two paths to enhance throughput neutrality and reduce overhead messages of IEEE 802.11g sensor nodes in a dense network.

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Last but not least, I would like to dedicate this work to the flowers of my life, my lovely kids Ali and Hawraa.

Uday Al-hamdany

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ACK	Acknowledgment
ACO	Ant Colony Optimisation
AODV	*Ad hoc* On-demand Distance Vector Routing
BER	Bit Error Rate
B-MAC	Berkely-MAC
BS	Base Station
CBR	Constant Bit Rate
CCA	Clear Channel Assessments
CH	Cluster Heads
CSMA	Carrier Sense Multiple Access
CSMA/CA	CSMA with Collision Avoidance
CSMA/CD	CSMA with Collision Detection
CTS	Clear To Send
DSR	Dynamic Source Routing
E-MAC	Eyes MAC
ETX-metric	Expected Transmission Count Metric
GPS	Global Positioning System
GW	Gateway
Hop-count	Hop Count Metric
IEEE	Institute of Electrical and Electronics Engineers
LAN	Local Area Network
LEACH	Low Energy Adaptive Clustering Hierarchy
L-MAC	Lightweight MAC
LQI	Link Quality Indicator
MAC	Medium Access Control
MANET	Mobile Ad-hoc wireless Network
MP-OLSR	Multi-path Optimised Link State Routing
Multi-hop	Multiple hop
Multi-path	Multiple path
PER	Packet Error Rate
PHY layer	Physical layer
QoS	Quality of Service

RERR	Route-error
RREP	Route-reply
RREQ	Route-request
RSSI	Received Signal Strength Indicator
RTS	Request To Send
SINR	Signal to Interference and Noise Ratio
SIR	Signal to Interference Ratio
SlotCA	Slotted Channel Access
S-MAC	Sensor-MAC
SNR	Signal to Noise Ratio
TC	Topology Control
TDMA	Time Division Multiple Access
TPC	Transmit Power Control
Tx_{power}	Transmission Power
Tx_{Range}	Transmission Range
WiFi	Wireless Fidelity
WSN	Wireless Sensor Network

CHAPTER 1: INTRODUCTION

1.1 Background

The need for distributed networks used in real-time monitoring and remote sensing has been growing in recent years. There has also been significant change in electronics and wireless communications. These two factors have necessitated the development of Wireless Sensor Network (WSN) technology [1]. Several technologies have been used to construct WSNs: embedded system technology coupled with sensor technology, and wireless communication technology. Sensor networks have the advantages of consuming less energy and less cost enquiries compared to other networks, such as *ad hoc* networks [2]. These advantages can enhance the sensor networks applicability in harsh and risky environments, as well as prolong their lifetime operations even when using batteries as the main energy supply. These advantages also make the sensor network applicable in a broad range of operations, including smart home automation [3], monitoring of industrial control [4], health care, agricultural systems, environmental fields [5], biomedical functions [6] and the diagnosis of mechanical failure [7].

The components of a WSN include sensor nodes, which sense, process and store data, as well as perform routing activities. The second component is the sink, or Base Station (BS), that links the sensor network to an existing communication infrastructure or internet such that it delivers the sensed data for further processing. The third component is the wireless communication medium, which links the sensor network to the communicating nodes. The wireless communication medium can be suited to various forms based on the specific requirements of its application such as agricultural applications [8, 9]. Figure1.1 presents a typical structure of a WSN.

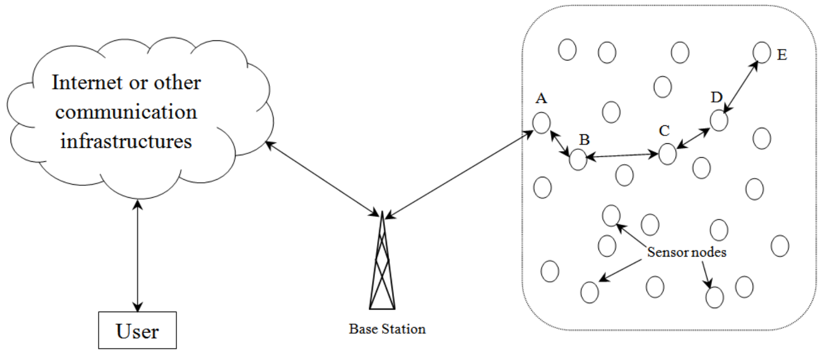

Figure1.1 Typical WSN structure.

Every sensor node senses the surrounding physical environment and transmits the collected data through an established route to the sink. Sensor nodes have relatively short transmission ranges which may increase the possibility of relaying data streams over several intermediate nodes to reach the destination by multi-hop topology, since they have limited energy resources such as batteries [10]. Data processing and transmission operations of a sensor node consume considerable energy, and batteries can be drained by the process of network operation.

WSNs contain hundreds to thousands of sensor nodes distributed over an extensive area. The nodes constantly communicate with each other, even when the network infrastructure is not present. Typically, network topology can be changed based on node or link failure as well as poor channel conditions due to the need of effective management of network topology through routing protocols. WSNs must be designed with the ability to sustain performance such that the performance of the network ought to be unaffected, even in dense networks. Thus, network density also challenges the development of routing protocols for WSNs [11].

When some nodes are deployed in certain applications of WSNs, the magnitude of the problem grows even greater. An example is in the field of surveillance applications, where sensor nodes are deployed in difficult, challenging and dangerous environments. Sensor node batteries cannot be recharged or replaced, as serving a large area by such nodes would be

costly and impractical. The limited source of energy thus can be considered the major challenge in the development of WSNs. One effective operation factor that has direct impact on the WSNs performance is the energy efficiency, the reason of necessitating the implementation of power management strategy. In this strategy, a small number of hops should be utilised to reduce the amount of energy consumption [12, 13].

One of the major challenges in WSNs is to reduce energy consumption while maintaining throughput. It is logical to use Transmit Power Control (TPC) to reduce power consumption by using multi-hoping, but this result in throughput reduction. Throughput neutrality can be obtained if the flow-out data rate from a region is equal to the region flow-in data rate such that there must be enough paths to eliminate the throughput reduction due to multi-hoping. Using two or more non-interfered paths may offer possible solution to maintain overall network throughput as well as reduce end-to-end delay.

1.2 Aims and objectives

The aim of this thesis can be abbreviated by the following objectives:

1. This thesis aims to utilise a multiple hops in high-density WSN in order to minimise their transmission power, reduce the overall power consumption and hence prolong the network lifetime.
2. This thesis aims to design an efficient multi-path routing protocol that has the ability of keeping throughput neutral for multi-hop low-power WSNs.

Increasing the number of hops will in turn reduce the throughput by a factor of N. This is due to the store and forward techniques used by single-transceiver/single-channel IEEE 802.11g sensor nodes. The key to manage this reduction is using multiple parallel paths. Also, reducing the transmission range is result in a doubled or tripled energy saving depending on the transmission frequency. Moreover, forwarding and routing information strategies are required to select an optimal multiple path routing protocol.

The aims and objectives of the current study will be targeted by addressing the following key research tasks:

- Determining the number of hops required to save energy and the number of paths needed to maintain the overall network throughput.
- Examining the effects of the number of hops on the throughput and energy consumption of a single-channel/single-transceiver WSN.
- Identifying the optimal multi-path routing protocol.
- Analysing/investigating the throughput neutrality in both cases using a multi-path and a single-path routing protocols.

1.3 Structure of the thesis

The overall structure of the study takes the form of six chapters, including this introductory chapter. As it has already been shown, Chapter 1 provides a general background on the WSNs and highlights the scope of the current study. Chapter 2 includes three important sections:

1. The first section presents a literature review on dense WSNs.
2. The second section provides a detailed and extensive study about TPC protocols. In this section, an extensive table is provided that lists relevant TPC protocols and their potential shortcomings in maintaining throughput.
3. The third section outlines the current multi-path routing protocols, as well as the advantages and disadvantages of the multi-path routing protocols, with and without TPC.

Chapter 3 begins by laying out the theoretical dimensions of the research, and then looks at the main findings to specify the contribution of the current study and find the optimal topology for the proposed algorithm. Chapter 4 provides a description and an analysis of the selected TPC with multi-path routing protocol in order to design a novel TPC protocol for

high density WSNs to reduce energy consumption, as well as maintain throughput based on the findings and the developed model in Chapter 3 and Chapter 4, Chapter 5 presents the simulation results of energy efficiency and throughput neutrality in both single-path and multi-path scenarios. Finally, Chapter 6 draws conclusions, and suggests some useful recommendations for future works to be conducted to this research study.

CHAPTER 2: LITERATURE REVIEW

2.1 Preliminaries

The aim of this chapter is to describe the current state of the art on Transmit Power Control (TPC) and multi-path routing protocols for IEEE 802.11 Wireless Sensor Networks (WSNs). Section 2.2 gives an overview of WSNs, and then two aspects of the relevant topics are explored. The first part of this chapter looks at optimal TPC for wireless networks (Section 2.3). The second part, beginning at Section 2.4, presents the use of multi-path routing protocols in WSNs. Finally, Section 2.5 summarises and concludes this chapter. Figure 2.1 shows the structure of the literature review chapter.

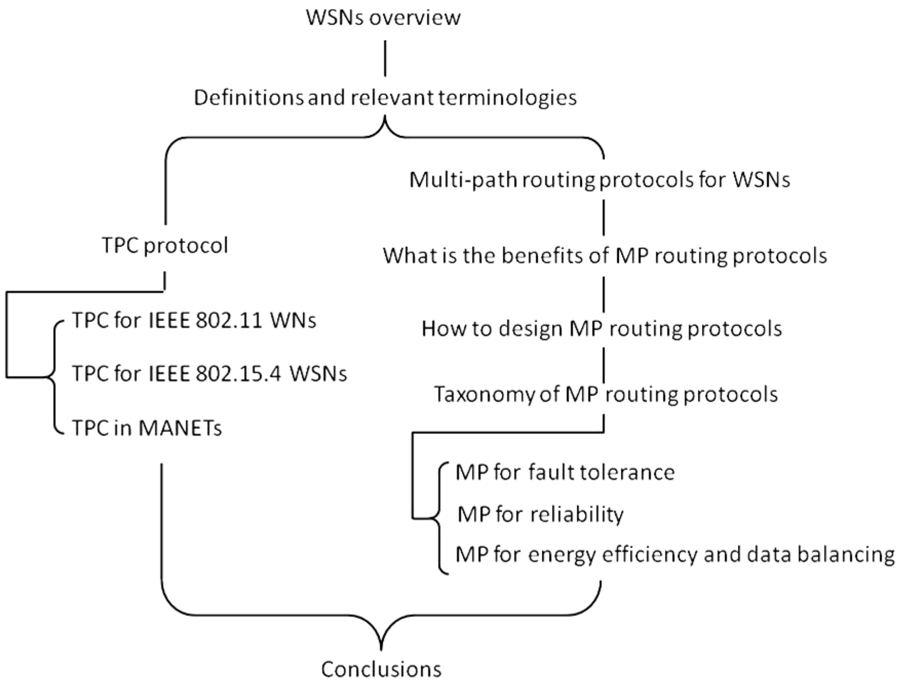

Figure 2.1 Structure of the literature review chapter.

2.2 An overview of WSNs

Recently, there have been rapid developments in WSNs. A WSN is a distributed network composed of small sensing devices. Each device is equipped with a microprocessor, memory and a short-range wireless channel [14–16]. A standard wireless channel is shared by all sensor nodes, which necessitates the need for efficient Medium Access Control (MAC) processes, without ignoring the other existing features, such as the network topology.

A typical sensor node is made up of a sensing stage, a processing stage, a radio frequency transceiver stage, and most importantly, a power supply compartment. Figure 2.2 presents a diagram of the stages of a sensor node.

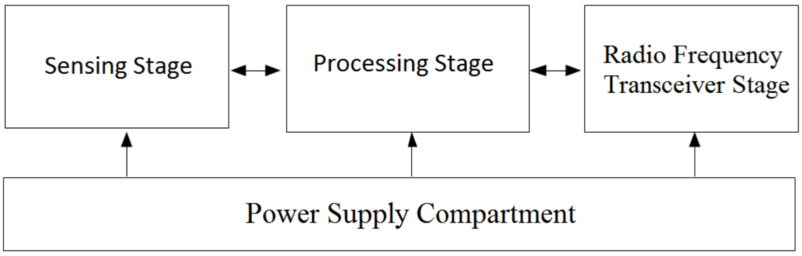

Figure 2.2 Diagram of the stages of a sensor node.

The processing stage includes a microprocessor and the storage memory. It is the brain of the system and controls the operations in all the other stages. The processing stage also processes simple data. In the sensing stage, sensors are connected to the processing stage and the focus is on converting and exchanging the gathered data into a form that can be readily processed by the processing stage. An analogue-to-digital converter gathers analogue information from the outside environment, and transforms it into a digital format ready for interpretation by the microprocessor. The exchange of data streams between the sensor nodes takes place in the radio frequency transceiver stage. This data exchange occurs through a wireless medium [8].

Since these different stages have different power input and consumption needs, they require a power supply that will supply appropriate input power for each use. Each of these stages involves variations in the current consumption that must be accurately provided by the power supply compartment. The area in which the sensor node is to be used can also dictate additional relevant stages or components. For example, a location finding system, which enables the accurate identification of the geographical information of a sensor node, can also be added, depending on the required application [9]. However, the physical challenges sensor nodes face constrains the design of single-channel/single-transceiver IEEE 802.11 WSNs.

Some of these constraints include the use of directed antenna and the multi-channel/multi-transceiver [17–21]. Utilising the directed antenna hardware in such systems to reduce wireless interference leads to additional designing costs of WSNs [17]. Although, a multi-channel method also reduces wireless interference and enhances network throughput, it may be insufficient to reduce the negative effects caused by channel interference for certain applications in addition to the high cost [18–20].

The main supplier of energy for sensor nodes is the batteries which have a limited capacity as power sources [10]. Since, processing and exchanging data in any sensor node consume a considerable amount of energy; the battery's energy can be drained by such operations. For example, when some nodes are deployed in the field of surveillance applications such as deserts which are difficult and dangerous environment, the sensor nodes' batteries cannot be recharged or replaced. Replacing the batteries of all nodes covering a large area is impractical and costly process, and thus, shows the major challenge in the development of WSNs [21].

Recently, the prevalence of energy resource inefficiencies in WSNs has been projected to pose significant challenges in the development of effective WSNs. Regarding such an issue to develop WSNs can enhance energy efficiency and network reliability, given that modern devices are expected to be more compact. To limit power losses at each sensor node, system components must be optimised and compatible with TPC protocols without affecting other features such as interference, throughput and data delivery rate [12, 13]. Research studies continue to focus on networking abilities, prolonging the network's lifetime and energy savings. Though energy saving has dominated WSN research, there are considerable interests in real-time applications such as multimedia applications that consume high rates of energy. This poses further challenges related to the network effectiveness such as network density and end-to-end delay [22].

In practice, WSNs can range from a few nodes to hundreds to thousands of nodes distributed over an extensive area. The nodes constantly communicate with each other, even when there is a lack of network infrastructure. Typically, the network topology can be changed by node failure and poor wireless channel conditions. As a consequence, this needs effective network topology management by suitable MAC and routing protocols [23].

It is necessary to briefly describe the existing protocols and relevant terminologies prior to starting an in-depth study of TPC protocols; we begin by relating common MAC methods:

- Time Division Multiple Access (TDMA) [24]: This is a time splitting protocol that shares a channel in time. It serves to allocate transmit and receive opportunities by dividing available frequencies into a number of timeslots. More often than not, this is a centralised process where a controller assigns how and which nodes are allowed to transmit and usually avoiding interference at a cost of extra complexity and overhead.
- Carrier Sense Multiple Access (CSMA) [25]: This is a MAC protocol that distributes and checks the medium channel activity prior to transmitting data on a shared frequency channel. This is the most common method of random access onto a channel.
- Lightweight MAC (L-MAC) protocol [25]: This is a TDMA protocol for WSNs, and it is a modification of Eyes MAC (E-MAC). Each sensor node in L-MAC selects only one timeslot through sequential slot reservation from single-hop neighbours. L-MAC notifies adjacent nodes through control message transmissions. L-MAC protocol was proposed to reduce multi-hop latencies and enhance energy efficiency.
- Sensor-MAC (S-MAC) protocol [26, 27]: This protocol splits time into a transmitting period and a listening period. Periodic sleeping consistent with S-MAC enhances the energy efficiency of WSNs.

- Berkely-MAC (B-MAC) protocol [28]: B-MAC is the default sensor node dedicated MAC protocol which manages the sensor nodes sleep/active periods, by utilising long-period for sleeping mode and regular short-periods to check the current communication activities. This protocol limits collisions through many features such as low-power listening and Clear Channel Assessments (CCA).

2.3 TPC protocols

TPC is a method of reducing the transmit power of a transmitter in order not to overwhelm a receiver as well as reduce power use at the transmitter. Hence, TPC is a commonly used energy conservation method. For multi-hop WSNs, TPC has been challenging, attracting much research in this area. A transmitter applies TPC in an attempt to utilise the least possible power necessary to reach its destination, and occasionally minimises wireless interference. TPC therefore not only conserves transmission power, but also reduces interference between sensor nodes and prolongs the network’s lifetime. Previous studies proposed that TPC is expected to manage power consumption in dense WSNs [29–31]. Therefore, in order to utilise the least possible power while maintaining throughput, it is required to reduce energy drain and prolong the lifetime of wireless sensor nodes.

An example of TPC in IEEE 802.11 WiFi networks is shown in Figure 2.3

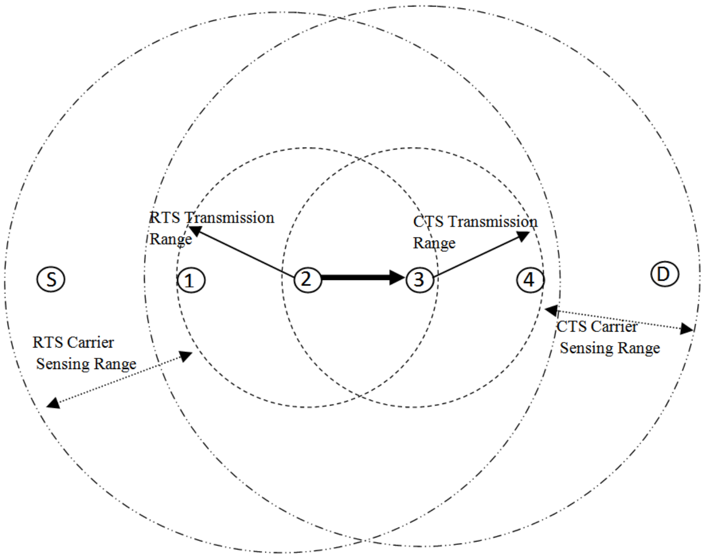

Figure 2.3 Carrier sensing range [32].

IEEE 802.11 suffers from high level of collision due to transmitting control messages at the maximum power level. As shown in Figure 2.3, after exchanging control messages between the transmitter-receiver nodes, Node 2 wants to transmit data to Node 3, Node D is not able to sense the transmission of the data between those nodes because Node D is in the carrier sensing range of Node 3 but not in the transmission range of Node 3. Thus, when Node D wants to transmit data, a packet collision can occur if Node 3 is a destination. This problem is also known as the hidden node problem. Using TPC here can significantly avoid the data collision and minimise the power consumption.

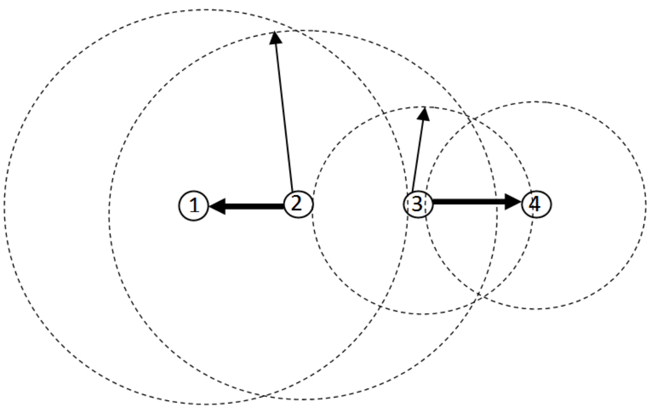

Figure 2.4 Multiple transmitting power level for different nodes.

The advantage gained through the above process maybe negated if TPC is not coordinated properly. Figure 2.4 shows that using multiple transmit power levels at different nodes may possibly raise data collision probability. For example, Nodes 1 and Node 2 utilise higher transmitting power level than Node 3 and Node 4. Node 1 and Node 2 cannot sense the data transmission when Node 3 exchanges data with Node 4. Thus, when Node 3 and Node 4 exchange their data but Node 1 and Node 2 also exchange their data by using a maximum transmission power level at the same time.

TPC has been applied in different contexts. Figure 2.5 shows a classification of the common TPC protocols that are considered in this thesis.

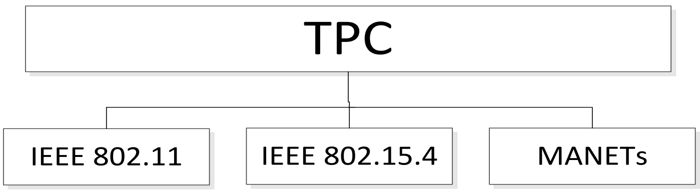

Figure 2.5 Classification of the common TPC protocols.

2.4 TPC for Wireless Networks (WNs)

TPC protocols can be organised based on three categories: IEEE 802.11, IEEE 802.15.4 and MANETs.

2.4.1 TPC in IEEE 802.11 WSNs

TPC protocols are widely used with IEEE 802.11 standards for wireless networks [23, 33]. A number of studies have revealed that single-channel/single-transceiver IEEE 802.11 MAC protocols fail to perform effectively in these environments with regard to energy efficiency and throughput neutrality. Current research findings have prompted future research to focus on TPC protocols that are suitable for in multi-hop WSNs without throughput reduction [33].

Kwon *et al.* [34] argued that a 'cross-layer strategy' is essential to achieve energy efficiency and consistent routing protocol within WSNs. This included the TPC strategy in the physical layer (PHY), the networking layer or as it is commonly known as the routing protocol, the MAC layer, as well as the re-transmission of control messages. The proposed system was built based on the adaptation of the transmission power in each node depending on the channel gain. The simulation results indicated that the trade-off between extended network lifetime and reliability could be achieved by making use of the proposed algorithm within the respective layers. In addition, TPC can give optimal energy savings when any data lost is not re-transmitted again. This strategy does not assure significant gains in terms of overall throughput.

Zhao *et al.* [35] proposed a 'novel self-organising energy efficiency hybrid' protocol based on the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol [35, 36] that joins cluster-based architecture with a multi-hop topology. The clusters were self-organised such that Cluster Heads (CHs) communicate to a specific sink node instead of directly communicating with the next-hop adjacent node to minimise the transmitting power consumption. The simulation results showed that the proposed protocol minimised the energy consumption and prolonged the network lifetime. However, the residual energy depletion can be increased by the use of a multi-hopping in stationary nodes such as the sink and CHs. The residual energy of intermediate nodes near the CHs was also be depleted rapidly as a result of their regular handling of data from other nodes. However, this protocol requires modification of the cluster-based architecture with a multi-hopping in order to maintain the overall throughput in the network.

The question of how much of the total energy utilised in a network can be saved by an 'ideal TPC' protocol was addressed by Vales-Alonso *et al.* [26]. A theoretical model was developed by defining L as the ratio for energy utilised in a network with TPC to that without TPC. The

L ratio was then compared to the MAC protocols such as L-MAC and S-MAC (as mentioned in Section 2.2). It was concluded that no considerable energy savings were achievable by using TPC for S-MAC; however, a maximum energy saving of 20 percent could be achieved when using the TDMA-based L-MAC. Vales-Alonso *et al.* [26] also stated that these results cannot be applied to every MAC protocol, and thus further simulations must be performed to investigate other MAC protocols to validate the results. According to Gurses *et al.* [25], it is possible to enhance network and link capacities by combining TPC algorithms with CSMA in wireless multi-hop networks. A mathematical model was formulated to consider the distances of transmitter-receiver pairs, hop-count metric (number of hops) and the network density. The results indicated that the proposed TPC protocol enhanced the overall network capacity by an average of 15 percent or more when compared with standard CSMA for varying network densities.

Viswanathan [37] proposed an 'adaptive link-per-link TPC' algorithm for a developed multi-hop IEEE 802.11n networks (with an Atheros chipset). The algorithm modifies transmission power to solve exposed and hidden node problems in order to limit interference levels between the sensor nodes and improve network performance. The algorithm was developed by adjusting the power transmission levels based on link margin, data loss rate and received signal strength. The experimental tests revealed that interference was avoided and network throughput was increased by 60 percent. Qiao *et al.* [38] built a 'novel per-frame-based intelligent TPC' protocol based on the minimum energy transmission strategy (MiSer) to solve the hidden node problem of the IEEE 802.11a/h DCF systems. The objective of MiSer is to find the optimal transmission power offline and create a lookup table that is used at runtime. It calculates an optimal transmission power for each data packet by using an energy level lookup table. The simulation results showed that MiSer behaves better than other strategies compatible with Request-to-send/Clear-to-send (RTS/CTS) in a sparse network

density. The TPC protocol with MiSer was found to be more efficient compared to the PHY adaptation rate approach without TPC. However, this study did not solve the hidden node problems which needs extensive modification of the TPC and cannot achieve throughput neutrality.

Ramchand *et al.* [39] introduced a new TPC model in multi-hop networks for calculating the node power consumption in a specific region, and then examining the proposed protocol against B-MAC. The main idea in this study was to make sensor nodes in sleep mode (i.e. remain switched off) for long time periods, then to activate them after regulated time periods to assess their communication behaviour. The results showed that the network throughput increases owing to the optimal data exchange, but such a node discovering process is not energy efficient. The simulation scenarios were conducted only for low network density, as the protocol performs poorly at high network density. This model thus, needs modification of the MAC to alter throughput and to extend the network lifetime. Tang *et al.* [40] proposed a TPC with a trade-off between channel reuse and data transmission rates for IEEE 802.11a wireless LANs. The proposed protocol was designed to run the TPC and offer possible solutions by using Slotted Channel Access (SlotCA) which split the channel into two periods, one is used by TPC-compatible devices and the other allocated to legacy devices utilising the latter timeslot. The simulation results revealed that TPC protocols improved throughput by up to 92.7 percent.

Choi *et al.* [41] suggested a ‘distributed TPC’ protocol to address wireless multi-hop network problems for a distributed network. The proposed protocol was established to select the required transmission power levels individually based on link quality for each hop to maximise overall throughput. The results revealed that the distributed TPC improves throughput gain in a multi-hop network and minimises the transmitting power consumption by enhancing transmit power adjustments in all active nodes. However, throughput gain is

still limited in terms of using the multi-hoping. A realistic energy consumption model was proposed by Kim *et al.* [42] based on TPC in distributed IEEE 802.11 wireless networks. The proposed model improves energy trade-off at the PHY and MAC layers by using a numerical analysis method. The simulation results showed that the distributed TPC is able to enhance the network throughput and minimise the total power consumption.

Harold *et al.* [43] investigated several existing protocols to improve throughput and minimise energy drain. An 'Enhanced Power Control MAC (EPCMAC)' protocol was proposed for wireless *ad-hoc* networks, in which the nodes trade-off between the optimum levels of the transmitting power. The transmitting power level was calculated based on the minimum carrier sensing range, the maximum channel capacity and the signal-to-interference ratio (SIR). The simulation results showed that the EPCMAC protocol was able to achieve a high data delivery rate per joule. This implies that the EPCMAC protocol has the ability to reduce power consumption and improve the throughput of the network.

A new 'Adaptive Transmission Power controlled MAC (ATPMAC)' protocol was proposed by Li *et al.* [44], for the single-channel/single-transceiver IEEE 802.11 to enhance throughput for wireless *ad-hoc* networks. ATPMAC implemented a new strategy in dealing with data exchange. Such that, the node allowed to handle its data concurrently, if it is not interfered with other nodes, without generating additional overhead messages. The proposed ATPMAC was simulated in NS-2.29, and the results were compared to the 'Power control MAC (POWMAC)' protocol which was developed by Muqattash *et al.* [45]. In POWMAC, the signal was transmitted over a channel in a particular radio transmission range without loss by using an Access Window (AW) to allocate a power level for a sequence of control message exchanges before several concurrent data packets broadcasting can be initiated. The size of the AW is automatically adjusted based on node location and the information of the destination node's surrounding area. The results have shown that ATPMAC enhances the

throughput of multi-hop wireless networks by approximately 136 percent compared to POWMAC. In extremely dynamic and mobile scenarios the POWMAC protocol may face strict degradation in performance. Next, we will look at transmit power control in conjunction with IEEE 802.15.4.

2.4.2 TPC in IEEE 802.15.4 WSNs

The IEEE 802.15.4 standard defines PHY layer properties and MAC layer specifications for wireless networks aimed at low power consumption of low-rate wireless personal area networks [27, 46]. The standard is designed to present a low-cost, low-complication and low-power wireless connectivity, making this best enabling technology for WSNs [47, 48].

Lee *et al.* [46] suggested an 'Adaptive Transmit Power Control (ATPC)' protocol to reduce control message overhead by employing both open-loop and closed-loop feedback systems in order to attain reliable routes without excessive control messages. All the nodes in the open-loop feedback system estimate the link quality. The nodes then reimburse the link quality's degradation by utilising a TPC protocol. In the closed-loop feedback system, an additional control message was employed to obtain a suitable TPC. In the mentioned protocol, the Received Signal Strength Indication (RSSI) was measured by the transceiver interface. The experimental results showed that the link quality changed periodically, depending on the fluctuations in the received signal strength. However, the ATPC was applied to a small-scale network rather than the common large-scale WSNs' topology and hence the conclusions that can be drawn are limited. A TPC Management (TPCM) scheme was designed by Tantubay *et al.* [48] based on Link Quality Indicators (LQI) readings for ZigBee nodes. LQI readings are taken as the ratio of the received signal strength to the summation of interference and noise power. The simulation results indicated that the TPCM scheme gives good network performance, including low level of packet loss, jitter, delay and power consumption with

high throughput. However, TPCM estimates distance among nodes using link quality indicators readings which gives inaccurate results.

A 'TPC with a realistic radio energy model' algorithm was proposed by Kamarudin *et al.* [49]. The optimal power level to communicate with the BS was selected automatically based on the estimated received power level and calculated path loss factor. The results of simulation and modelling platforms indicated that the lifetime of the wireless network was prolonged by the TPC protocol through the use of the 'free space path loss model'. A high level of efficiency with an improvement of about 8.7 percent was achieved after deploying the sensor nodes in agricultural and farm areas. Nevertheless, this study has some limitations including the single environment case study, and the pre-existing features in WSNs including end-to-end throughput were not fully considered.

Caijun *et al.* [50] proposed another energy-efficient protocol referred to as an 'Adaptive TPC with an enhanced L-MAC (ADTPC-LMAC)' protocol based on a slotting time system. In order to obtain timeslots, nodes were required to run in three states:

- State one: the initial state, refers to routing's initialisation;
- State two: the discover and wait state, whereby nodes wait randomly for an interval time prior to selecting the timeslot;
- State three: the active state, which follows the success of timeslot gaining.

The simulation results revealed that the behaviour of ADTPC-LMAC provided long network lifetimes as well as more reliable transmission of data streams. However, ADTPC-LMAC concentrates on energy saving during idle listening and overhearing, which are associated with less power use that in the receive and transmit modes.

Das *et al.* [51] proposed a 'novel query-driven routing', which uses the optimal power balancing technique for WSNs. This algorithm determines the transmitting power levels for

each selected node as the next-hop adjacent node with maximum residual energy. The results showed that prolonging node lifetime and energy savings of IEEE 802.15.4 WSN were achievable. However, there is a negative impact on the throughput of the network because of the use of multi-hopping. Another TPC algorithm was developed by Messier *et al.* [52] based on the use of a cross-layer optimisation theory in the PHY and link layers for IEEE 802.15.4 WSNs in which a 'Cross-Layer Power Control (CLPC)' algorithm was defined. Simulation results revealed that best network performance was achieved when the upper layers enhanced the reliability of the PHY layer. A significant share of energy savings was achieved by the novel CLPC algorithm compared to the original CLPC algorithm. In this study, however, no comparisons with other common existing MAC protocols were provided.

Cheng *et al.* [53] proposed a 'Multi-Level Power Adjustment (MLPA)' algorithm to prolong the network and node lifetimes, and ensure network connectivity for IEEE 802.15.4 WSNs. In this algorithm, a minimum power level was set for neighboured sensor nodes and a maximum power level was set for distant sensor nodes. The process of MLPA involves three steps:

- Firstly, the sensor node recognises all adjacent nodes by the use of maximum power in order to ensure the connectivity of the network;
- Secondly, the node then adjusts the transmitting power to each node individually in order to identify the perfect power level applicable to adjacent nodes;
- Finally, by using a piggyback power adaptation strategy, the adaptation process can then be reduced.

Following the change of network topology, the network was dynamically updated after the movement of the nodes. The run time of the network was then maintained, with the first and second steps being repeated. As demonstrated by simulation results, a reduction of up to 45

percent of the transmission power was attained, which was observed to be increased to about 90 percent following the use of a free space path loss model.

An enhanced control approach using a TPC protocol in IEEE 802.15.4 WSNs was proposed by Meghji *et al.* [12, 13, 54, 55] by testing multi-hoping to minimise the power consumption and to prolong the network lifetime. The transmitting power was adjusted to eight levels of the required power to maintain network connectivity based on the calculated signal strength and estimated distance between transmitter-receiver pair. The experimental results demonstrated that no significant energy savings were obtained when transmitting data streams in multi-hop channels compared to single-hop channels. Also, up to 23 percent energy conservation was attained in single-hop networks due to their ability to send data steams at a minimum power factor with maintaining network connectivity. To reach such a conclusion, the short-range/single-hop was applied in sparsely WSNs.

Moreover, the major platform for wireless networks are the Berkeley motes as it can be noted in most literature sources regarding TPC protocols. The Mica2 mote is a well-known commercial product among researchers and system developers [28]. It is quite useful for understanding the features of this technology, which will be described in the next paragraphs in relating to TPC algorithms for Mica2 motes.

Correia *et al.* [28] proposed two novel TPC techniques which rely on data exchange between nodes for the dynamic adjustment of transmit power. This involves piggybacked power level requests for data streams and *ACK* messages. The other technique rates the actual transmission power based on the various readings of the RSSI, which is useful to determine the signal strength through calculating the medium noise and other incoming information. In this case, the ideal transmission power is the lowest power level that requires delivering the data streams to the destination node. The test-bed results showed that the throughput was

enhanced by 14.2 percent, and the power consumption was reduced by 27 percent. According to Correia *et al.* [56], their work was continued in [28] with the proposal of two TPC techniques. In these techniques, the hybrid method determines the required transmission power by using sequence corrections to enhance the link quality. In the second technique, the 'Adaptive Exponentially Weighted Moving Average (AEWMA)' protocol was developed to determine the actual transmission power of subsequent transmissions which was expressed as the noise average. The results showed that energy savings increased by 57 percent on B-MAC with the use of the proposed TPC techniques.

Wang *et al.* [57] proposed a 'Sleep Scheduling based on TPC (SS-New)' protocol which was developed based on the old sleep scheduling (SS-Old) protocol to prolong network lifetime and reduce data loss through the adjustment of active and sleeping times, and every node sets its own active/sleep time based on the residual energy. The simulation results indicated that the proposed algorithm solved certain problems related to the node in terms of data loss avoidance. Zhang *et al.* [58] proposed a 'Fuzzy Control Theory Protocol (FCTP)' to reduce the energy depletion in the multi-hop WSNs in which, a closed-loop control system is applied where each node transmitted *HELLO* (Identity) messages periodically with an equal initial transmit power level. Prior to receiving the next exclusive-identity message, all other nodes receive the message then a reply feedback was given as an *ACK* message. The source node computes and compares the number of these exclusive messages received at a period versus the previous period. The results indicated that the proposed model conserves more energy and prolongs the network lifetime to a greater extent than the TPC models that are already in use. However, the network throughput in WSNs was not considered in the addressed study.

Lin *et al.* [59] suggested an 'Adaptive TPC (ATPC)' protocol which chooses transmitting power levels based on link quality and surrounding environment. On-demand feedback is also applied to ensure the adjacent nodes connectivity. ATPC was tested in MICAz motes,

and the results revealed that in a real environment, ATPC could achieve up to 98 percent end-to-end Packet Error Rate (PER) for both rainy and dry seasons, and an energy savings of about 46.4 percent in the transmitting mode. Kim *et al.* [60] proposed an 'On-Demand TPC (ODTPC)' protocol for WSNs to find the optimum transmitting power level through reducing the initialisation overhead and providing optimum link quality. The link quality between each node pair was calculated based on exchanging *DATA* and *ACK* messages between adjacent nodes. The test-bed results showed that higher energy consumption was reduced by ODTPC in every node compared to other TPC protocols such as ATPC [59], and the lifetime of the network was also prolonged. However, the network throughput was not considered in the proposed ATPC and ODTPC protocols, while it is an important feature of WSNs.

In the next section, we will look at the application of TPC for MANETs that do not use IEEE 802.15.4.

2.4.3 TPC for MANETs

This section briefly outlines TPC protocols in MANETs. The abbreviation MANETs refers to a group of mobile *ad-hoc* wireless nodes with the ability to route packets between nodes [27, 63]. TPC protocols that were developed to be used in MANETs are mostly not compatible with WSNs due to mobility, transmission range and battery lifetime limitations.

Nie *et al.* [61] proposed a 'Power Control for Control Frame (PCCF)' protocol for IEEE 802.11 *ad-hoc* networks to calculate the transmitting power for the RTS frame according to the following three variables.

- The carrier sense threshold;
- The receiving threshold (the minimum value required for proper decoding);
- The maximum transmission power required.

The distance between nodes and data transmission power can be calculated by finding the Signal-to-Interference and Noise Ratio (SINR). The results showed that PCCF worked well to prolong node lifetime, increase throughput gain and reduce energy consumption as well as delays for low-density scenarios. Abduljaleel *et al.* [27] designed a novel per-frame TPC protocol referred to as the 'Adaptive Energy-efficient MAC (AE-MAC)' algorithm in *ad-hoc* IEEE 802.11 single-channel/single-transceiver networks to enhance network throughput. The mechanism of AE-MAC is based on adjusting transmission power for each frame in a sequential order such that data transmission interferences with other sensor nodes can be minimised. AE-MAC utilises TPC depending on data payload values and the network interference. It calculates and tabulates the optimal power levels as nodes transmit control frames (RTS/CTS) during data frame transmission progress. The transmitting power levels were adjusted based on RTS and CTS signal strengths. Although, the simulation outcomes showed that AE-MAC provided minimal throughput improvements, an interference reduction and increased energy savings could be achieved. However, transmitting power of control frame is not significant for it to be compared with data frames.

Gautam *et al.* [62] developed an 'Enhanced TPC scheme (ETPCM)' to reduce transmitting power consumption in mobile *ad-hoc* IEEE 802.11b sensor networks. The ETPCM protocol was built based on the RSSI readings, and hence, the transmitted power was synchronised appropriately in accordance with the estimated distance between mobile nodes and calculated values. The simulation results indicated that ETPCM enhanced throughput while decreasing delays and jitter. ETPCM was also found to use less energy compared to the standard TPC. Zhu [63] suggested a TPC based on radio transmission range protocol to reduce transmission power consumption depending on path loss model function and the distance between nodes for multi-hop WSNs. The simulation results showed limited energy saving improvements when increasing the number of hops, and significant enhancements in energy efficiency were

attained through the use of an optimal transmitting range without considering the network throughput.

Table 2.1 provides a summary of previous studies conducted to TPC protocols for wireless network communication. Note in the table that most protocols do not address the loss of throughout when applying TPC and the aim is simply to reduce the energy used by the network. In this work, we propose reducing the energy used through TPC but maintaining throughput through the setup of alternate paths between the source and destination.

Table 2.1 Summary of TPC protocol previous studies.

Ref.	Approaches	Methods	Objectives	Key findings	Key gaps
[34]	A cross-layer strategy based-TPC	Mathematics & Simulation	TP[1] is adjusted based on channel gain	1. Enhance energy efficiency; 2. Prolong lifetime 3. Reliable connectivity	Throughput and network density
[35]	A novel self-organising hybrid protocol	OPNET	The clusters were self-organised such that CHs directly communicate to a specific sink node instead of the next-hop	1. Enhance energy efficiency; 2. Prolong lifetime	Throughput and network density
[26]	Theoretical model for MACs protocols	Mathematics & Simulation	Calculate *L* ratio for energy gain with TPC and No-TPC	enhance energy efficiency for L-MAC protocol only	Throughput and network density
[25]	A TPC based on CSMA	Mathematics & MATLAB	Calculate back-off time based on distance, hop-count and network density	1. Enhance energy efficiency; 2. Eenhance network and link capacity; 3. Avoid data collision	Throughput
[37]	An adaptive link per-link TPC	Mathematics & Simulation	TP is adjusted based on link margin, data-loss rate and received signal strength	1. Enhance energy efficiency; 2. Avoid interference; 3. Enhance throughput	Network density
[38]	A novel per-frame-based intelligent TPC	NS 2	Calculate an optimal transmission power for each data stream by a lookup table	Enhance energy efficiency	Throughput high density network
[39]	A new TPC model	MATLAB	Utilise sleeping mode for long time intervals then use active mode at regulated intervals.	1. Enhance energy efficiency; 2. improve throughput in low density WSN	Throughput in high density WSN
[40]	A basic TPC	Scenargie	TP trade-off between channel reuse and transmission data rate	1. Enhance energy efficiency; 2. Improve throughput in dense WLAN	
[41]	A distributed TPC	Mathematics & Simulation	TP is adjusted based on link quality for each hop	1. Enhance energy efficiency; 2. Improve throughput	Network density
[42]	Realistic energy consumption model	Mathematics & Simulation	Utilise cross-layer between MAC and PHY	1. Enhance energy efficiency; 2. Improve throughput	Network density
[43]	EPCMAC	NS 2	Calculates pulse power level periodically based on min carrier sense range, max channel capacity and SIR	1. Enhance energy efficiency; 2. Improve throughput	Network density
[44]	ATPMAC	NS 2.29	The node stops data exchange concurrently, if it interfered others to reduce overheads	1. Enhance energy efficiency; 2. Improve throughput; 3. Aavoid interference	Network density
[45]	POWMAC	Mathematics & Simulation	Utilise AW to allocate TP level for control frames based on node location(distance)	1. Enhance energy efficiency; 2. Improve throughput	Network density
[46]	ATPC	Hardware Experimental	Calculate the link quality based on the RSSI readings in open and closed-loop	1. Enhance energy efficiency; 2. Avoid extra overhead	Throughput and network density
[48]	TPCM	QualNet 5.0	Calculate received signal strength ratio from LQI readings with the summation of interference and noise power	1. Enhance energy efficiency; 2. Improve throughput; 3. Reduce data loss, delay and jitter	Network density
[49]	TPC with realistic radio energy model	OmNET++	TP is adjusted based on receiving power level and path loss factor	1. Enhance energy efficiency; 2. Prolong lifetime; 3. Avoid data collision	Throughput and network density
[50]	ADTPC-LMAC	NS 2.34	Each node operates on three states: initial-state, discover-and-wait-state, and active-state to enable slotting time system	1. Enhance energy efficiency; 2. Reduce delay and jitter; 3. Reliable data delivery	Throughput and network density

[51]	An optimal power balancing technique	Simulation	Select the next hop based on maximum residual energy	1. Enhance energy efficiency; 2. Prolong lifetime	Throughput and network density
[52]	Novel-CLPC	Optimisation theory	Set MAC and MAI routing based on cross-layer of MAC and PHY	Enhance energy efficiency and network performance	Throughput and network density
[53]	MLPA	Mathematics & Simulation	Set low TP level for close adjacent node and high TP level for distant nodes	Enhance energy efficiency and network connectivity	Throughput and network density
[54]	Enhanced controlled approach TPC	NS 2 & testbed	TP is adjusted based on the calculated signal strength and estimated distance between transmitter-receiver pair.	1. Enhance energy efficiency; 2. Prolong lifetime	Throughput
[28]	Two novel TPC techniques	Mathematics & Testbed	TP is adjusted based on various readings of the RSSI	1. Enhance energy efficiency; 2. Improve throughput	Network density
[56]	i) Hypred TPC protocol & ii)AEWMA	Mathematics & Testbed	TP is adjusted based on link quality, power noise average, and signal power in both receiving and transmission	Enhance energy efficiency	Throughput and network density
[57]	SS-TPC	Simulation	Schedule sleep mode for long timeslot at each node	1. Enhance energy efficiency; 2. Prolong lifetime; 3. Reduce packet loss	Throughput and network density
[58]	FCTP	Testbed	TP is adjusted based on the exclusive messages number received per period, versus previous period.	1. Enhance energy efficiency; 2. Prolong lifetime	Throughput and network density
[59]	ATPC	Testbed	TP is adjusted based on the link quality, utilise on-demand feedback technique	1. Enhance energy efficiency; 2. Limit PER	Throughput and network density
[60]	ODTPC	Testbed	TP is adjusted based on the link quality that computed through messages exchanging	1. Enhance energy efficiency; 2. Prolong lifetime	Throughput and network density
[61]	PCCF	NS 2	TP is adjusted based on the carrier sense threshold, receiving threshold and the maximum TP required as well as SINR	1. Enhance energy efficiency; 2. Improve throughput; 3. Prolong lifetime; 4. Reduce delay	Throughput in high network density
[27]	AE-MAC	QualNet v5.0	TP is adjusted based on data payload values and network interference	- 1. Enhance energy efficiency; 2. Avoid interference	Throughput and network density
[62]	ETPCM	QualNet v5.0	TP is adjusted based on estimated and calculated RSSI reading	1. Enhance energy efficiency; 2. Improve throughput; 3. Reduce delay and jitter	Network density
[63]	TPC scheme based on radio transmitter range	Mathematics & Simulation	TP is adjusted based on path loss function and distance between nodes.	Enhance energy efficiency	Throughput and network density

[1] TP stands for Transmitting Power

2.5 Routing protocols for WSNs

The majority of the existing routing protocols within WSNs are developed based on single-path routing protocols with no consideration of the consequences of the existent data traffic load values. This scheme assures that each source node uses a single-path to transmit data into the destination node. In WSNs, single-path routing protocols achieve low data rate aggregation depending on the network capacity limits [22]. Efficient single-path routing does not exploit all the available resources of the network, while it is not efficient for an energy-conserving approach due to the reasons listed below.

- The establishment of a new route necessitates the consumption of more energy if node failure or compromised paths occur (i.e. low fault tolerance) [64], and malicious nodes in the network can corrupt the data [37];
- The same shortest path is always selected by the single-path routing protocol leading to energy depletion at each node in the established path [65, 66];
- Data loss through congestion in a single-path is common [67].

Single-path routing is less reliable compared to multi-path routing as a result of the environmental interference, resource limitations and malicious nodes. While, transferring data through a multiple path protocol leads to a significant enhancement in the reliability, and having more than one path increases the chances of recovering from a node failure or a compromised path [64]. Increasing node density in WSNs enhances a multi-path routing protocol that establishes multiple paths between source-destination pairs [24]. The established alternative paths are used to provide the necessary network resources for high-load traffic situations. Occasionally, the source node may employ one path for data transmission and one alternative path for

node or link failure which is known as fault tolerance. In addition, the multi-path routing protocol has been designed to enhance the reliability of data transmission, reduce network congestion, provide fault tolerance and support Quality of Serves (*QoS*). In WSNs, the limited resources such as battery lifetime and memory capacity as well as the transmission range produce new challenges within the design of multi-path routing protocols [33, 68]. The existing multi-path routing protocols used for conventional wireless networks (*ad-hoc* networks) are not directly compatible with WSNs. This has promoted research into WSNs which has led to the development of multi-path routing protocols regarding the compatibility with sensor networks.

2.5.1 Benefits of incorporating multi-path routing protocols in WSNs

In WSNs, the data traffic loads may cause network congestion which can negatively impact the network performance [69, 70]. To reduce the probability of network congestion through distribution of data load traffic over alternative paths, multi-path routing protocols enable load balancing for densely WSNs [71–73]. Enhancing data load traffic balancing across sensor nodes also enhances energy efficiency, which prolongs the nodes and network lifetime. The link capacity is limited due to the utilisation of a shared channel within a single-path scheme such that the use of other alternative paths increases the interference and data collision [74, 75] leading to limiting the design of efficient multi-path routing protocols. To solve such a problem, various techniques including location-aware routing [76, 77], multi-channel data transmission [18–21] and directed antenna [17] are incorporated to reduce the channel interference. Location-aware routing protocols are proposed to minimise overheads due to increased applications of localisation techniques. Multi-channel communication also enhances network throughput through a reduction in channel interference by the incorporation of channel switching. Additionally, directional

antennas are proposed to reduce wireless channel interference. However, combining WSNs means additional costs, and may be insufficient to reduce the negative effects caused by channel interference for various applications.

Another important consideration for designing multi-path routing protocols is *QoS* which refers to network performance such as delay, link-capacity, overall throughput and data rate [24, 78]. Unlike single-path routing protocols, multi-path routing protocols maintain *QoS* for the required application. For example, for real-time applications such as multimedia, data streams are exchanged through high link-capacity/low delay paths, while low link-capacity/high delay paths are used for non-real-time applications. Thus, single-channel wireless networks enhance the overall throughput as well as the data transmission rate by using multi-path routing protocols in WSNs.

The network resource limitation, sensor node mobility and interference represent common challenges towards the development of reliable data delivery [79, 80]. The incorporation of multi-path routing protocols provided high resilience against node or link failure in order to enhance the reliability of data transmission in WSNs. Using alternative paths can maintain data streams when the sensor nodes in the active path are unable to handle their data streams to the destination node. Multi-path routing enhances data forwarding via the availability of an alternative path between the source-destination pair which limits the interruptions in the case of node or link failure. Multi-path routing protocols are incorporated concurrently to enhance the reliability of transmitting data in the network by utilising multiple routes [81]. Two main methods are to be found in the literature to enhance reliability. The first method is based on transmitting several copies of the original data within a variety of routes, which enhances data recovery from any node or link failure to assure data

communication reliability through the establishment of alternative routes, but it faces high levels of resource depletion. The other method depends on the data-coding method when the source node adds some information to the original data copy leading to consequent distribution of the identified data streams between the different routes. Recovery of the original data helps to enhance data exchange from each node, which improves the data delivery rate at the network. In the event of node or link failure, the data reliability will be activated through recovering original data copies, which have already been received by the destination node.

2.5.2 Designing an efficient multi-path routing protocol

A multi-path routing protocol is utilised to establish a sufficient number of optimal paths as it enhances network performance. Each multi-path routing protocol integrates various factors that assist in establishing multiple paths and enhancing data traffic load balance over the alternative paths. These factors are briefly explained as follows.

2.5.2.1 Number of hops

In WSNs, path discovery is used to locate next-hop intermediate nodes, then incorporates them to establish non-interfered multiple paths between source-destination pairs. The multi-hoping is employed as it utilises a limited transmission range, and consequently, enhance its efficiency and reliability. It also identifies the importance of intermediate nodes, which enhances its energy efficiency in WSNs.

2.5.2.2 Path discovery

A path discovery scheme is used to select the required intermediate nodes in order to establish multiple paths between the source-destination pair. In this stage, various

parameters are incorporated within the existent multi-path routing protocols to improve the development of routing decision-making.

The main parameter is the number of non-interfered multiple paths, which has to be incorporated in the proposed multi-path routing protocols [78, 82]. The discovered paths are identified as node-disjoint (Figure 2.6), link-disjoint (Figure 2.7) and partially-disjoint paths (Figure 2.8).

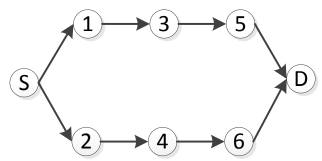

Figure 2.6 Node-disjoint paths.

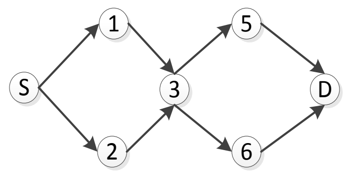

Figure 2.7 Link-disjoint paths.

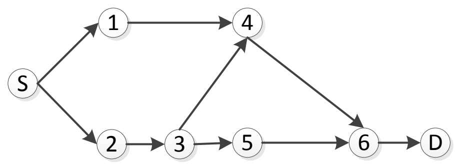

Figure 2.8 Partially-disjoint paths.

From Figure 2.6, it can be seen that any node or link failure affects only the active path without any impact on another path. This form of path disjointedness enhances the network resources. However, randomly distributed sensor nodes limit the effective discovery of large sets of node-disjoint paths between the source-

destination pair. Figure 2.7 shows link-disjoint paths which incorporate various common nodes through a shared channel between the paths. Any node failure within a set of link-disjoint paths deactivates various paths that share the failed node. Figure 2.8 shows partially-disjoint paths which incorporate multiple paths that share several links among different routes in which node or link failure within a set of partially-disjoint paths affects other routes. However, establishing non-interfered multi-paths can be easily performed by identifying the pros and cons of different types of path disjointedness. The required application and network density are related to effective decision-making regarding utilising node-disjoint, link-disjoint or partially-disjoint paths [85, 86].

2.5.2.3 Alternative path discovery

The main objective of designing each multi-path routing protocol is to identify a specific number of alternative paths to advance the required application performance. Identification of an optimal path discovery method is necessary to estimate the required number of alternative paths, which is a significant step in the multi-path routing protocol design, and enhancing protocol performance. Multi-path routing protocols primarily utilise only the optimal path for transmitting data, and then includes other alternative paths such as backup or recovery paths for fault tolerance [82–84]. However, many multi-path routing protocols take advantages of employing alternative paths to enhance the reliability of data exchange as well as increasing data traffic load balance effectively [87–91].

2.5.2.4 Network resource depletion

Minimising resource depletion can prolong the network lifetime, and enhance the longevity of the sensor nodes in WSNs. The network resources depletion occurs when using the optimal multi-path to send several copies of the original data in order

to enhance data reliability and fault tolerance. However, the balancing of the data traffic load over all discovered alternative paths can conserve network resources [92].

2.5.2.5 Path maintenance

A path re-discovery is needed to enhance network performance. This thus, necessitates the path maintenance within multi-path routing protocols. The mechanism includes the following scenarios:

1. In the event of node or one active path failure;
2. In the event that all active paths have failed;
3. In the event that a specific number of active paths have failed.

First scenario uses path re-discovery, and thus produces higher overheads. Consequently, incorporation of a route re-discovery prior to the failure of all the active paths may enhance network performance. The third scenario identifies the trade-off between the pros and cons of the first and second scenarios.

2.5.2.6 Path failure detection

Multi-path discovery management provides path failure notification for the network layer to enable the recovery of paths. A number of routing protocols such as 'Dynamic Source Routing (DSR)' [93] and '*Ad-hoc* On-Demand Distance Vector Routing (AODV)' [94] has a path failure detection that removes the failed paths from the routing table, and thus, enables the route re-discovery. The source node is altered by *Route-error* (*RERR*) messages to detect the path failure. It is advisable to transmit a path failure notification to the transport layer to remove the detected path failure from the routing table, when designing the routing protocol.

It is necessary to briefly describe the existing routing protocols and relevant terminologies prior to starting an in-depth study of multi-path routing protocols; we begin by relating routing protocol types:

- Proactive routing protocols [95]: In these routing protocols, all nodes retain the network structure in their routing table. Each of the nodes exchanges routing information that is usually communicated as a ‘flood’ through the wireless channel. In the event that a source node desires a route to a destination, it acquires the path by utilising the topology data that it possesses. Nodes are regularly updated in the event that the topology of the node is altered. The benefit of this protocol is that the routes are always available without the overheads of route establishment. However, when the mobility rate in the network is high, the procedure is delayed. ‘Optimised Link State Routing (OLSR)’ protocol is one example of a proactive routing protocol [96, 97].
- Reactive routing protocols [37]: These protocols create routes between a source and a destination only when asked to do so by the source nodes. It does not require that the nodes retain the routes to uncommunicative destinations. Thus, the node only sends *Route-request (RREQ)* message to another node, and awaits the response from the destination node. The *RREQ* message is relayed over intermediate nodes to reach the destination node, which will then respond by a *Route-reply (RREP)* message that relays information pertaining to the adequate optimal path between the source-destination pair. As a result, the delay period is increased, as the source needs the topology data to present the optimal path before relaying the data. However, despite this, the procedure saves memory for each of the nodes.

This is because this category does not maintain the network topological information. Thus, the protocols do not communicate routing information regularly. Some examples of reactive routing protocols are DSR [93] and AODV [94]. Multi-hop links are created over the sequence nodes. In the event that any of the nodes changes its position, moving out of its transmission range when there is a weak signal or a faulty node within the network, then the path automatically fails. Compared to proactive routing, reactive routing is regarded more efficient as it discovers routes between the nodes only when they communicate.

- Hybrid routing protocols: These routing protocols take advantages of both the reactive and proactive nodes and increase network performance effectively [98]. In this instance, the protocols use proactive discovery in areas adjacent to the node, while using reactive protocols to communicate across nodes. An example of hybrid routing protocol is 'Multi-Path Optimised Link State Routing (MP-OLSR)' [98, 111, 112].

2.5.3 Categorisation of multi-path routing protocols for WSNs

There are many routing protocols that have been proposed for WSNs. These can be categorised in a variety of ways. In this work, we are mainly concerned with multi-path routing as this reduces interference and increase throughput in most cases. Figure 2.9 shows our categorisation of multi-path routing protocols that we have considered in this study.

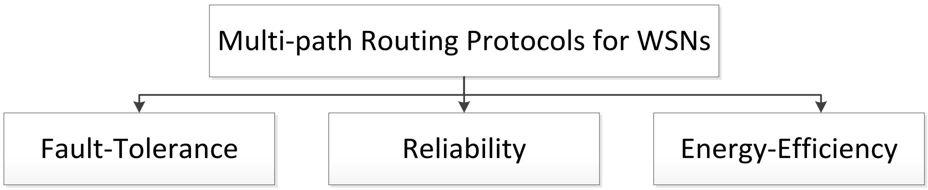

Figure 2.9 Classification of the multi-path routing protocols for WSNs.

2.5.3.1 Multi-path routing protocols for fault tolerance

For a single-path route, the network is compromised when any malicious attack occurs in the route. Multi-path routing integrates fault tolerance into the network by identifying a number of alternative paths. The node transmits data over multiple parallel paths, and if one of these paths is compromised by malicious activity, the destination node can receive the original data copy from the other alternative paths.

Intanagonwiwat *et al.* [99] proposed a 'Directed Diffusion (DD)' multi-path routing protocol to solve the node or link failure issues. The DD protocol is activated by the destination node through broadcasting *Interest* messages which include the information that is required to establish multiple paths. In this step, all the intermediate nodes identify the *Interest* messages exchanged from adjacent nodes to their next-hops. The receiver node appends the required data until reaching the source node after receiving an *Interest* message. In the subsequent steps, many alternative paths can be incorporated between the source-destination pairs, thereby; the source node matches the appended information in its interest table. Then the destination node receives the requested data stream from multi-path routes. The data stream enhances the optimal path establishment based on the lowest latency of the data. This requires reinforcing the destination node of the selected path by relaying of *Reinforcement* messages to reach the oppositely directed source node. The destination node continues to send *Interest* messages within the established paths

leading to enhancement in the path maintenance. Other paths are incorporated to enhance and give high fault tolerance if the active path fails to relay data. The results show that the DD protocol enhances the data delivery rate and minimises the end-to-end delay when the node or link failure occurs via the active path. However, this protocol limits the overall throughput as it uses one path for data relaying, and sending intensive *Interest* messages may cause greater energy depletion.

Ganesan *et al.* [83] proposed a 'Braided Multi-path Routing (BMR)' protocol to provide fault tolerance in WSNs which has similar mechanism of DD protocol. Figure 2.10 shows a schematic diagram of BMR protocol.

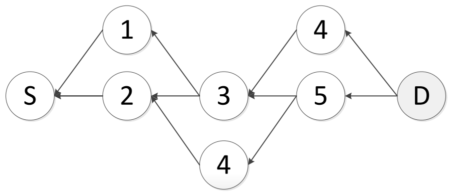

Figure 2.10 Schematic diagram of BMR protocol.

In Figure 2.11, Node D transmits the primary path *Reinforcement* message to Node 5 which then sends the message to the next-hop until it reaches Node S. After that, Node S and the intermediate nodes along the primary path establish an alternative path around their next-hop adjacent node. Node D and intermediate nodes relay alternative path *Reinforcement* messages, which are broadcasted to the next-hop adjacent node to reach Node S. This leads to the establishment of a backup path. It can be found from the results of implementing BMR protocol that the energy cost of the alternative paths is dependent on the network density. However, the energy consumption is high due to the relatively high energy required to maintain the alternative paths. Since BMR was developed based on the DD mechanism; hence the limitations pertaining to DD are similar in BMR.

2.5.3.2 Multi-path routing protocols for reliability

Multi-path routing protocols identify the ratio of the received data to the transmitted data, and this ratio is referred to as network reliability or goodput. In general, the single-path protocol has low reliability due to the influence of environmental effects, malicious nodes or resource limitations. Reliability can be enhanced by utilising multi-path routing to transmit data through multiple alternative paths. Also, node or link failure recovery is identified faster during multi-path routing as a comparison with single-path routing due to the availability of additional paths.

Lou [100] proposed the 'N-to-1 multi-path routing' protocol, which develops multiple paths from all sensor nodes to reach a specific destination node, based on a many-to-one mechanism. The N-to-1 multi-path routing protocol is initialised through two steps as listed below.

1. The destination node broadcasts *Route-update* messages in order to discover the primary path from each sensor node. Any intermediate node receives the *Route-update* message for the first time from an adjacent node, which is assigned as the parent node to be added to the routing table. This step is repeated until all sensor nodes identify their primary path to reach the specific destination node.
2. Each sensor node tries to discover additional alternative paths to reach the same specific destination node. The main aim of this step is to enhance the exchange of information relating to the multiple paths discovered between the nodes. The source nodes splits data traffic loads to several copies via the established alternative paths.

However, the N-to-1 routing protocol is similar to single-path behaviour that constraints link capacity and data throughput. Lou *et al.* [101] proposed a hybrid

multi-path (H-SPREAD) protocol for secure and reliable data collection by employing a combination of the N-to-1 route establishment mechanisms and a hybrid multi-path routing protocol for WSNs. In H-SPREAD, the original data copy can be sent to reach the destination node which shared by other nodes when the original ones or links fail. This protocol incorporates the N-to-1 routing protocol to establish multiple paths leading to an increase in the interference. However, a high level of data loss-rate occurs as a consequence of interference, causing a reduction in the data delivery rate. H-SPREAD consumes more power when exchanging secured data in alternative paths, as well as it does not balance the data traffic load.

Deb *et al.* [88] proposed a 'Reliable Information Forwarding multi-path (ReInForm)' routing protocol, which duplicates data to enhance WSN reliability. At first, the source node identifies the data reliability depending on the priority of the gathered data in order to reach the destination node. Afterword, the source node appends an extra field to the data frame, called the Dynamic Packet State (DPS) field which includes Bit Error Rate (BER), hop-count and required reliability. Next, the source node calculates the required alternative paths that are needed to ensure reliability of the information gathered based on the attached DPS field. This method is continuously repeated until the transmitted data streams reach the destination node. However, in addition to the resource limitation problems in WSNs, using ReInForm routing protocol is conducted with an increase in the energy consumption.

Huang *et al.* [91] developed a 'Multi-Constrained *QoS* Multi-Path (MCMP)' routing protocol to enhance reliability and reduce delay. MCMP scheme incorporates two steps:

- Each node selects a set of adjacent nodes that enhance the network reliability.

- Each source node identifies a set of paths from the chosen nodes.

The source and intermediate nodes should relay several copies of the original data streams to the destination node through different sub-paths. However, in the MCMP protocol, intermediate nodes identify the set of their adjacent nodes that meet the reliability and delay related to the data source, which disregards power use in the transmitting mode over each path. Bagula *et al.* developed [102] an 'Energy Constrained Multi-Path (ECMP)' routing protocol, which is a modified version of MCMP [91] that aims to constrain energy in WSNs, as well as enhance reliability and reduce delay. This protocol aimed to improve MCMP routing protocol by reducing energy consumption. Figure 2.11 shows an explanation of ECMP scheme.

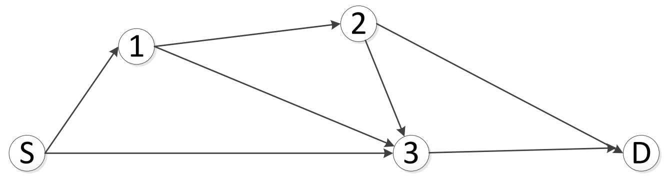

Figure 2.11 ECMP scheme.

As shown in Figure 2.11, the distance between Node S and Node 1 is short if compared with the distance between Node S and Node 3. The necessary energy to send data is dependent on the distance between the transmitter-receiver pair. The energy consumption of Node S is minimised by selecting Node 1 as the distance is shorter than Node 3. The results showed that MCMP and ECMP achieved equivalent delay and data delivery rates. Conversely, ECMP consume lower energy than MCMP protocol, but both of these protocols fail to account for WSN throughput.

Ben-Othman *et al.* [103] designed an 'Energy-efficient *QoS*-based multi-path routing (EQSR)' protocol for real-time applications to enhance the reliability and reduce the end-to-end delay. EQSR broadcasts *HELLO* messages to all nodes in the WSN.

During that, each sensor node gathers information related to the route cost. Next, the intermediate nodes use variables such as the residual energy level, buffer capacity and the signal-to-noise ratio (SNR) level to identify the most appropriate next-hop adjacent node to reach the source node. This step is rendered continually at the intermediate nodes until a *RREQ* message reaches the source node and establishes a primary path. After that, the destination node constructs extra alternative paths by broadcasting *RREQ* messages to adjacent nodes. Optimal paths are then selected based on the data delivery probability at all multi-path routes. In the final step, the source node balances its data traffic load through the selected paths, based on their delay. The results concluded that EQSR minimises end-to-end delay and enhances reliability. Nonetheless, the function of routing costs limits the number of paths with minimum interference levels.

2.5.3.3 Multi-path routing protocols for energy efficiency and data balancing

Frequent use of the optimal route increases the rate of energy consumption at sensor nodes within a single-path WSN. However, enhanced balancing of the data traffic load over a multi-path WSN can prolong the lifetime of the network by utilising the alternative paths for data exchange. Data traffic load balancing shares out the load over multiple paths by sending lesser amounts of data in an attempt to balance data traffic over the network and improve throughput. This section describes the most commonly proposed efficient multi-path routing protocols.

Lu *et al.* [65, 104] designed an ‘Energy-Efficient Multi-path Routing (EEMR)’ protocol to extend WSN lifetime by balancing data traffic loads. The source node broadcasts *RREQ* messages which incorporate different path IDs to establish multiple paths such that all the intermediate nodes choose optimal next-hop adjacent node to reach the destination node. The choice is based on the hop-count, the

distance between a sender-receiver pair, as well as the initial and the residual energies at each node. Once the destination node receives the first *RREQ* message, it enables a timer to reduce the route establishment time. When the timer timeouts, the path will be identified as a low quality path, and then neglected. The destination node then calculates the data rates of all the discovered paths based on the number of paths and the route cost of each path. The destination node incorporates *Assign* messages to inform the source node about the calculated data rate of each established path. The source node then sends its data stream when it receives the *Assign* messages. This protocol is proposed to prolong WSN lifetime through balancing of data traffic loads.

Hurni *et al.* [105] proposed an AOMDV-inspired protocol based on the multi-path version of AODV protocol [94] to achieve low latency of data relaying and high energy efficiency of WSNs. AOMDV-inspired protocol has the same route establishment of AODV which enables a new routing table to establish the multiple paths with the optimal number of hops. AOMDV works to enhance the routing table of all intermediate nodes to find the optimal next-hop adjacent node to reduce the latency of data exchange. The main results showed that AOMDV noticeably minimises interference and end-to-end delay. Maimour [106] designed a 'Maximally Radio-disjoint (MR2)' multi-path routing protocol to enhance the required bandwidth for multimedia applications. The strategy for discovering multiple paths is similar to other multi-path routing protocols that can be found in the references [84, 85, 99]. After discovering multiple paths, the active nodes report their adjacent nodes acting as passive nodes by sending *BePassive* messages to all adjacent nodes excluding their previous-hop and next-hop nodes to avoid any new path discovery and interference. The results showed that MR2 enhances the overall data rate by more than 70 percent in a comparison with a multi-path routing protocol that does not

consider the interference. However, AOMDV and MR2 protocols broadcast the routing information during the route establishment, leading to an increase in the overheads at the sensor nodes that consume high levels of energy.

Teo *et al.* [107] designed an 'Interference-minimised Multi-path Routing (I2MR)' protocol to deal with high data rate for wide bandwidth WSNs in order to balance data traffic load. In the I2MR protocol, the source node uses one backup path and two routes for data exchange with BS. Path discovery can be achieved by implementing the following three steps.

1. The destination nodes known as gateways (GWs) that represent the WSN backbone. Each source node selects a primary GW, and establishes the shortest route to be the primary path;
2. The primary interfering area is defined when the protocol allocates one and two hops adjacent nodes from the primary path's nodes;
3. The primary GW discovers the selected quadrants of the surrounding circle area in order to choose the secondary and backup GWs. These quadrants are chosen according to the source node location.

The source node establishes the secondary path and backup path from the nodes that are deployed outside the primary interfering area. Afterword, the source node data is relayed over both the primary path and secondary path. Such a process balances the data traffic load fairly. The results showed that the I2MR protocol has a better performance than the standard AODV protocol [94].

Wang *et al.* [76] designed an 'Energy-Efficient and Collision Aware (EECA)' multi-path routing protocol for WSNs based on the node location by using Global Positioning System (GPS) to minimise energy depletion and avoid data collision.

EECA establishes two parallel paths in both directions between the source-destination pair. The method works under the assumption that the number of nodes (*N*) is incorporated with a transmission range (*R*) within a two-dimensional area. The source node identifies two groups of nodes that satisfy three specified conditions:

1. Each node within the group should be close to the destination node.
2. All nodes should be located at one side of an end-to-end link.
3. The distance between each node of the two different groups must be greater than *R/2*, and the distance between two nodes in the opposite groups must be greater than *R* in order to avoid collision and interference on each route.

EECA assures that the distance between each couple of paths is greater than the interference range of the sensor nodes. The results showed that the ECCA protocol has high energy efficiency, good network performance and minimum delay. However, using GPS increases the cost of network localisation and the data overhead as well as energy usage.

Radi *et al.* [81, 90] designed a ‘Low-Interference Energy-efficient Multi-path routing (LIEMRO)’ protocol for minimum interference and enhanced performance of WSNs. The source node establishes the primary path based on some variables such as the adjacent node number, the residual energy at each node, the interference level and the expected transmission count (ETX) metric value. The ETX metric is defined as the probability of successful forward and backward data reception per the specific route based on the link cost. The LIEMRO protocol enhances the WSN performance through data traffic load balancing with dynamic route maintenance. Vidhyapriya *et al.* [108] designed an ‘Energy-Efficient Adaptive Multi-path Routing (EEAMR)’ protocol to extend network lifetime and reduce energy consumption by using data load balancing. The EEAMR protocol distributes the data load over multiple paths

based on the signal strength and the residual energy to ensure the energy consumption equality of each node. In other words, the source node allocates high data load to high residual energy path and less data load to low residual energy path to achieve uniform energy depletion in all alternative paths. The results showed that energy efficiency is enhanced by the multi-path routing protocol in high-density WSNs.

Ant colony routing algorithms are a form of swarm intelligence that imitates the cooperative behaviour performed by ants' life in the identification of the shortest path between the nest and food sources [31]. To illustrate the basics of the algorithm, ant X is on a forward route to search for a food source. It walks from the nest (source node) to the food (destination node). When ant X arrives at a node-joint-path, it has to determine the optimal path. While walking, ant X utilises pheromones along the route, and once the ant identifies food, it backs to the nest and consequently marks the return route. This enhances the identification of food by the rest of the ants, by following the pheromone trail. Xiu-li *et al.* [109] designed the 'Multi-path routing based on Ant Colony System (MACS)' algorithm to identify the optimal primary path and optimal alternative paths between source-destination pairs to prolong network lifetime. The forward ant seeks for parallel multiple paths, and if the intermediate node has been visited, the ant ignores the marked node and searches for another. However, if the node has not been visited by another ant, the ant evaluates the adjacent node to the destination node and updates the pheromone table. The backward ants update the pheromone table by following the forward ant and establishing the optimal multi-path. The results showed that the MACS algorithm enhanced energy efficiency, network performance and network lifetime. Saleem *et al.* [110] designed a 'Self-Optimised Algorithm using Multi-path Routing

(SOAMR)' protocol based on the 'Ant Colony Optimisation (ACO)' approach for WSNs to provide the best throughput and avoid data congestion by balancing a traffic load between two or more paths. This protocol discovers the optimal path with a minimum energy cost route to determine the shortest multi-path based on various factors such as delay, receiving data rate and residual energy of the next-hop adjacent node. In the event that the optimal path is not identified, the procedure is repeated to establish other paths. The results identified that WSNs can aggregate high data throughput with reduction in the data loss rate. However, SOAMR protocol does not consider the effects of network density and traffic load of the active nodes.

Zhang *et al.* [113] proposed a 'Load Balancing Multi-path Routing based on DSR (LBMRDSR)' protocol according to data load balancing and load-aware methods. The LBMRDSR protocol utilises the DSR algorithm for path discovery and route maintenance. Additionally, it uses the assumption which states that the congested data are equal across all the routes to utilise alternative paths over the entire data traffic load which can be found on the different paths. The simulation results showed that the LBMDSR protocol works better than both DSR and MRDSR in terms of data stream delivery rates as well as end-to-end delays. Despite this, the proposed LBMRDSR assumes, rather than considering, the effects of node or link failures due to data congestions.

The MP-OLSR protocol [98, 111, 112] is a hybrid multi-path routing protocol that merges proactive and reactive mechanisms. MP-OLSR exchanges *Topology Control* (*TC*) messages and *HELLO* messages to each node in order to update them regarding the topology of the wireless network. However, the MP-OLSR protocol does not keep a routing table that collects information periodically; it only identifies the

necessary paths when data packets are to be communicated. The MP-OLSR protocol is built based on two parts which are topology sensing and route computation.

- Topology sensing involves forcing the nodes to obtain the topology information of the network including link sensing, topology discovery and neighbour detection. This protocol integrates the targeted benefits by utilising OLSR protocol [96, 97]. The OLSR protocol minimises the number of *TC* messages by ensuring that the identified nodes, also called the Multipoint Relays (MPRs), are able to distribute their messages through the entire network. Furthermore, it minimises the size of the *TC* messages, as it communicates only with a subset of adjacent routes regarding their MPR selectors. This method minimises the amount of re-transmission of data streams in the communication of the messages.
- Route computation utilises the multi-path *Dijkstra* algorithm for multi-path routing using the information that it obtains from topology sensing. The active route is appended to the header of the data frames. The intermediate nodes read the data frame header and then relay the frame to the next-hop adjacent node. In addition, path recovery is introduced to manage the challenges of active routing.

MP-OLSR protocol does not always maintain a routing table for each potential destination in the network as it only addresses multiple paths when data streams are to be communicated within the network. The MP-OLSR protocol was designed based on the single-path OLSR protocol. The two protocols incorporate the same procedures when discovering the network topology, but a different mechanism within their routing through the data streams. In the OLSR protocol, the source node requires calculating the shortest path to the destination, and relays the data streams to

reach the next-hop adjacent node. The intermediate nodes relay the data streams in accordance to their routing table. In the MP-OLSR protocol, the source node requires calculating the alternative paths, and specifies one path in each data stream (the active path) prior to relaying data to the next-hop adjacent node. The intermediate nodes relay the data stream according to the initialised primary path leading to enhance the compatibility of the MP-OLSR routing protocol. However, the majority of multi-path routing protocols do not consider compatibility with their single-path version. Table 2.2 summarise the previously addressed studies of multi-path routing protocols that suitable for WSNs.

Table 2.2 Summary of multi-path routing protocols for WSNs.

Protocols	**Based-on**	**Energy consumption**	**Traffic load**	**Reliability**	**fault-tolerant**	**No of paths**	**Maintain /Recover**
DD [99]	-	Limited	Unbalanced	No	Yes	-	M[1]
BMR [83]	DD	Limited	Unbalanced	No	Yes	2	M
N-to-1 [100]	-	-	Balanced	Yes	No	-	-
H-SPREAD[101]	N-to-1	-	Balanced	Yes	No	-	-
ReInForm [88]	-	High	Unbalanced	Yes	No	-	-
MCMP [91]	-	High	Unbalanced	Yes	No	-	-
ECMP [102]	MCMP	Limited	Unbalanced	Yes	No	-	-
EQSR [103]	-	Limited	Balanced	Yes	Yes	-	-
EEMR [65, 104]	-	Limited	Balanced	Yes	No	-	M
AOMDV[105]	AODV	High	Balanced	-	No	-	M
I2MR[106]	-	Limited	Balanced	No	Yes	3	M & R[2]
EECA[76]	GPS	Limited	Balanced	Yes	No	2	-
LIEMRO[90]	-	Limited	Balanced	Yes	No	-	M
EEAMR [107]	-	Limited	Balanced	Yes	No	-	M
MACS[108]	ACO	Limited	-	-	No	-	-
SOAMR[109]	ACO	Limited	-	Yes	No	2	-
LBMRDSR[110]	DSR	Limited	Balanced	-	No	-	M
MP-OLSR[98, 111, 112]	OLSR	Limited	Balanced	Yes	Yes	3	M & R

[1] M stands for path maintenance; [2] R stands for path recovery

2.6 Conclusions

Based on the above literature review, useful conclusions and recommendations for further research works in this field can be highlighted.

- The integration of various applications necessitates the incorporation of specified transmit power level selection and traffic load balancing.
- Among the different standardised WSNs, single-channel/single transceiver IEEE 802.11g seems to perform effectively due the fact that it is cheap and has high performance, but it suffers from the problems of limited power resources such as irreplaceable/un-chargeable battery.
- A multi-hop topology is incorporated as it employs a limited transmission range, and thus enhanced efficiency and reliability of WSNs.
- It is of importance to consider the intermediate nodes' features in order to enhance the achievement of energy efficiency in WSNs.
- The energy efficiency witnesses significant improvements if the number of hops is optimised. However, increasing the number hops will reduce throughput by a factor of N.
- Multi-path routing enhances throughput as they relay data streams through alternative paths by balancing the data traffic load over alternative paths.
- A multi-path routing protocol can perform a key solution to prevent the limitations that identified through the integration of single-path routing protocol within the WSNs.
- Network density is a significant factor that affects the energy efficiency in WSNs based on the distance between the sensor nodes.

The key issues associated with the development of a novel TPC protocol for high density WSNs includes the following objectives:

- Developing a proper mathematical model which calculates the required number of paths to maintain throughput and the needed number of hops to reduce power consumption for high density WSNs.
- Selecting the suitable TPC protocol from the previously designed protocols in order to enhance energy efficiency by using multi-hop topology.
- Choosing the most efficient multi-path routing protocol in order to keep throughput neutral for single-channel/single-transceiver WSNs.
- Merging both TPC and multi-path routing protocols as well as considering the protocol compatibility to maintain throughput and save energy at the same time.
- Examining the proposed model against several simulation scenarios to cover both high and low network densities.

CHAPTER 3: METHODS AND PROPOSED MODELS

3.1 Preliminaries

In this chapter, we propose a problem formulation and obtain some preliminary results by conducting a number of case studies. Next, we elaborate on the operation of the proposed Transmit Power Control (TPC) protocol for high density Wireless Sensor Networks (WSNs) in order to save energy and maintain throughput. To save energy, the graphs and mathematical models are proposed to implement multi-hop topologies. Also, other models are presented to maintain throughput by using multi-path routing protocols.

3.2 Problem formulation and case studies

We assume a sensor network with nodes distributed over an area. The nodes are distributed randomly across an area with a uniform distribution.

Figure 3.1 shows a path spanning the region in a single-hop if the maximum power of the node transmitter is used. This is the route between Node S and Node D. Hence, in this case the throughput is a maximum at 100% (or 1). Also notice that using the maximum power will result in the maximum interference region. In this case, the transmitting Node S is interfering with 10 nodes if one includes the receiver D as one of the 10.

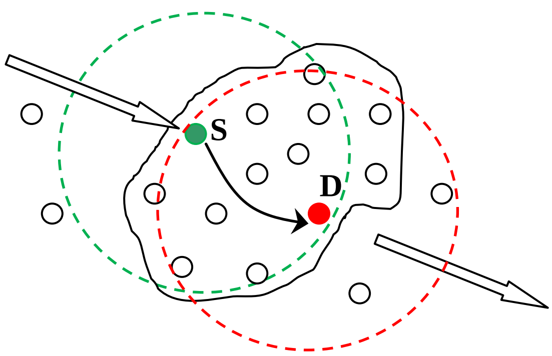

Figure 3.1 A single-hop with maximum transmission range.

Now let's consider a multi-hop case with multiple parallel independent paths as shown in Figure 3.2. In this case, we span the region in two hops by reducing the transmission range of the transmitter, this results in the node using less transmitting power. But to span the region, 2 hops are required now; hence another node will need to retransmit the same data in order to reach the destination. There is still an advantage in this, as power is usually related to the inverse square, cube or higher of the distance (depending on frequency), halving the range will usually result in using a quarter of the original power. Hence overall, there is a power saving (depending on the receive power of the intermediate node).

Although, there is a major disadvantage because effectively half the throughput is lost as the same data is being transmitted twice. This disadvantage can be mitigated if the network can discover two independent paths.

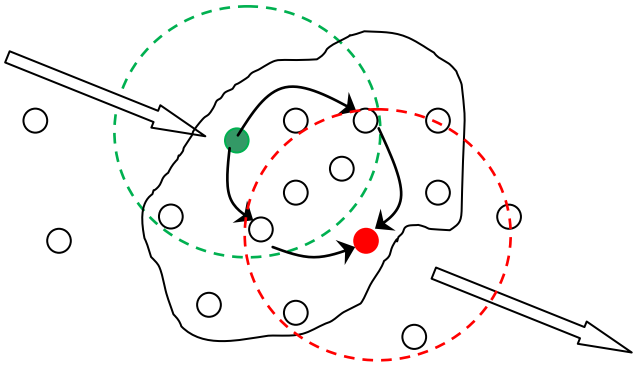

Figure 3.2 Two-hop with reducing transmission range.

Hence, our proposed approach is to design a protocol that is capable of discovering multiple paths as well as use TPC to reduce transmitter power and hence exploit multi-hopping. The hypothesis of this thesis is that throughput can be maintained while the overall energy of the network can be reduced if this is the case. Also note that reducing the transmit power will result in less interference to surrounding nodes.

The assumptions of such a system are:

- Each sensor is a homogeneous and has a unique ID, and has an omni-directional antenna with free space propagation model.
- The transmission range of each sensor node is a variable, so that it can use the minimal transmission power that is required to keep connectivity by using TPC.
- The number of parallel paths is more than one path. Hence, the assumption here is that the network is dense enough for this purpose; otherwise if the network has low density then power can only be saved in the network at the cost of throughput.
- The packets or frames have the same size and they take only one timeslot (*t*) to transmit.

We will present our case studies in two parts: energy-efficiency (Section 3.3) and throughput neutrality (Section 3.4).

3.3 Energy efficiency in a WSN

This thesis assumes a single-channel/single-transceiver IEEE 802.11g PHY layer, and also assumes that all sensor nodes have adaptable transmission power levels. Each node is capable of sending a data packet at the lowest required power towards the next-hop and utilises multi-hoping in order to reach a destination node. The transmission power consumption can be minimised by reducing the transmission range (as a multi-hop topology) instead of long-range transmission (as a single-hop topology).

Upon transmission, an electromagnetic wave can be modelled as a sphere spreading out away from a source point. Hence, the energy of the wave front dissipates with the

square of the area. This is known as path loss or transmission loss. This is true for most frequency ranges. The rate of loss is defined as the path loss exponent (α). Depending on the frequency, the path loss exponent value is generally in the range of 2 to 4 (α=*2* for a free space propagation model, and α *=4* for higher frequency ranges. This is mainly due to higher absorption rates from atmospheric conditions and not just due to the wave front spreading out). Only in some special cases the path loss is actually lower than 2. α is less than 2 in a tunnel that can act as a waveguide and hence the energy is maintained per unit area of wave front. In this section, we formulate equations to calculate the *relative* total power consumption (P_T) and *relative* power consumption for each node $P(n)$ in terms of the number of normalised transmissions. $P_{tx}(n)$ is defined as the relative transmit power consumption, while $P_{rx}(n)$ is the relative receive power consumption at receiving mode for n nodes. The number of hops is defined to be h, the number of paths is k, and the d is defined to be the distance ratio that divides the one hop distance by the maximum possible transmission range as it is illustrated in Figure 3.8.

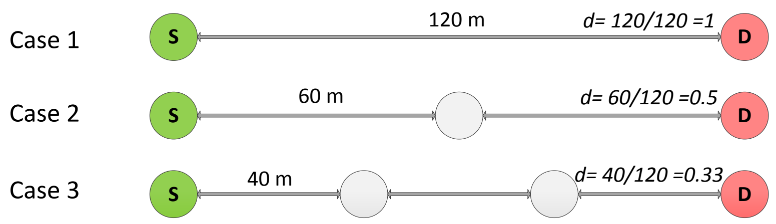

Figure 3.3 Distance ratio for single and multiple hops topology.

In Figure 3.3, Node S represents the source node, and Node D represents the destination node. The maximum transmission range is shown in Case 1 such that data is delivered in a single-hop. In which, d is maximum and equal to one. In Case 2, d is halved because the transmission range is also halved based on the intermediate node located between the source-destination pair. In Figure 3.3: Case 3, d is equal to one

third due to the existence of the two intermediate nodes located between the source-destination pair. For generalisation, the following equation can be used to calculate *d*.

$$d = \frac{1}{h} \tag{3.1}$$

where, *d* is the distance ratio, and *h* is the number of hops where we assume that the total transmission range is split equally between hops.

Here, we interpret the single-hop transmission power as relative to the maximum transmission power (P_{max}) of the node. For example, Figure 3.4, Case 4 shows that if the maximum transmission power is 1 and the *d* is halved, then each node only consumes a quarter of P_{max}. Hence, the relative end-to-end transmitting power consumption (P_T) is half if the number of transmitting nodes *n* is two (as shown in Case 5).

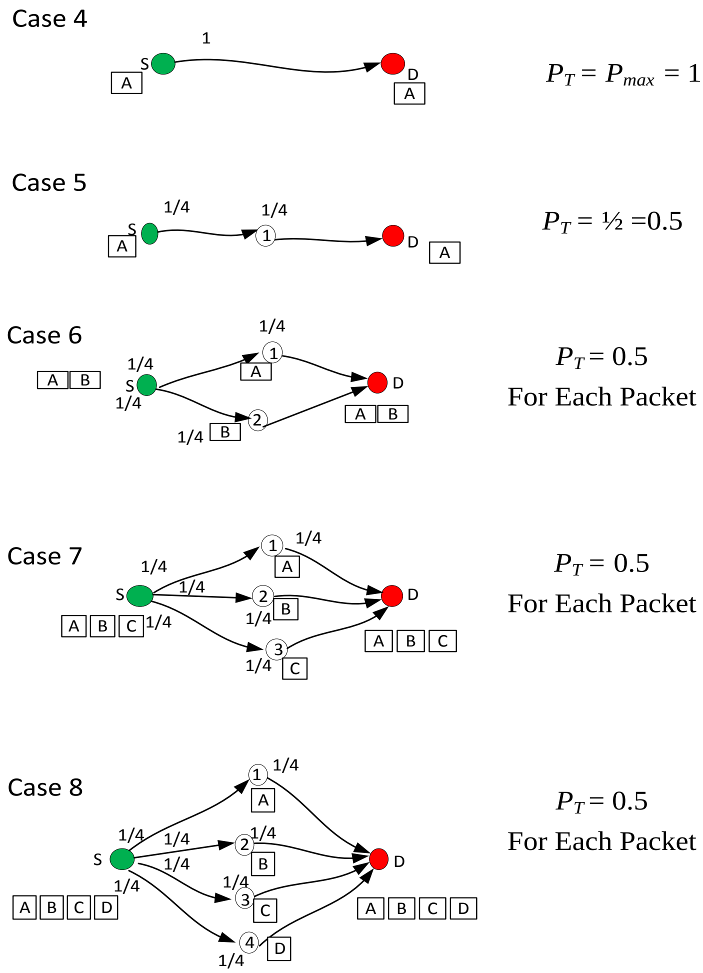

Figure 3.4 Single-hop and two-hop case studies.

In Figure 3.4: Case 6, the relative total transmitting power consumption is also 0.5 while one packet is delivered to Node D over a two–hop topology. However, if two packets are relayed over two parallel paths the relative total power consumption is 1 which is similar to Case 5 for sending two packets. The power consumption of each packet delivery process in Case 7 is also equal to 0.5 of the maximum power that is consumed in a single-hop topology. Similarly, when utilising two-hop/4-path topology, the consumed power is 0.5 of the maximum power for each packet. This means that increasing the number of paths leads to the same power consumption, and hence the two paths topology will be used to indicate the other multi-path topologies.

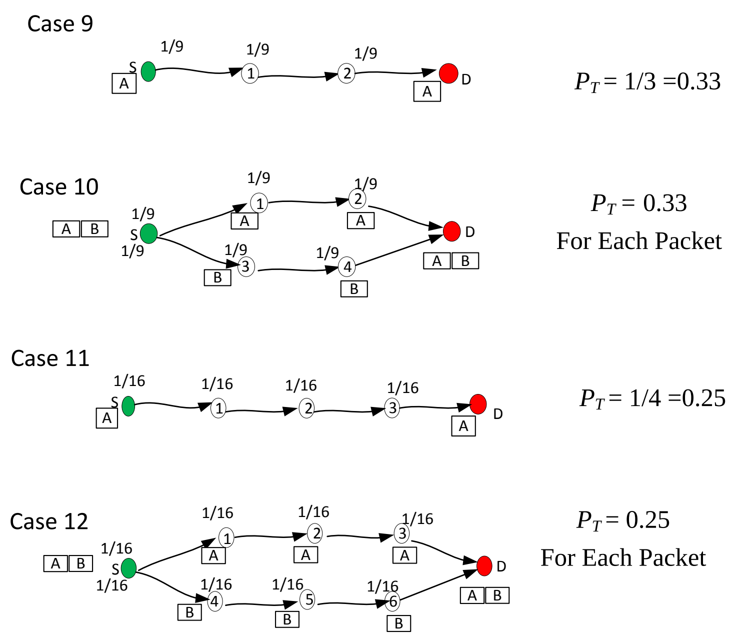

Figure 3.5 Three-hop and four-hop case studies.

Taking a closer look at Figure 3.5, Case 9 shows that using a 3-hop topology in a single-path route can reduce the total power consumption to a third of the maximum power, in Case 10, the power consumption in multi-path topologies is also reduced to be 0.33 of the maximum level. Again, Cases 11 and 12 show that using a 4-hop topology at each route gives 75% improvement in power saving. It is important to note here that the power consumption in a multi-hop topology is efficiently reduced while the number of hops is increased regardless of the number of paths. In addition, it is clear that the power used is inversely proportional to the number of hops and not the number of paths.

From the previous graphs, the maximum power consumption (P_{max}) with the distance and path loss exponent are used to find the *relative* power at each transmitting node:

$$P_n = d^{\alpha} \; P_{max} \tag{3.2}$$

where P_{max} is 100% (or 1), and the path loss exponent (α) is equal to 2, assuming that the free space propagation model is used.

We can generalise the equation to find the *relative* power consumption at each transmitting node.

$$P_n = \frac{1}{h}^{2} P_{max} \tag{3.3}$$

The *relative* total power consumption percentage is calculated by finding the consumed power at all transmitting nodes.

$$P_T = \sum_n P_n = \sum_n P_{tx}(n) \tag{3.4}$$

where, P_T is the relative total power consumption percentage P_n is the total power for each node, n is the number of active nodes, and $P_{tx}(n)$ is the total transmit power,

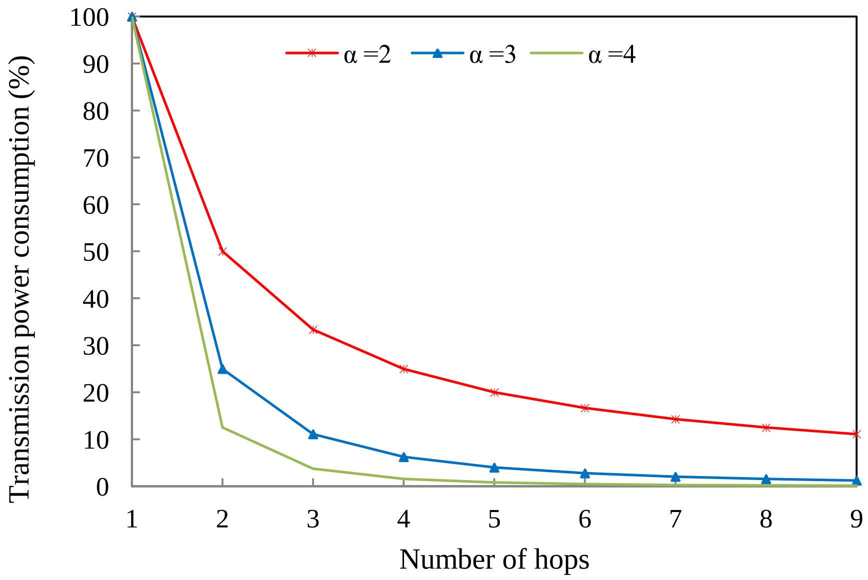

Figure 3.6 Transmitting power consumption percentages for α equal to 2, 3 and 4.

Figure 3.6 clearly shows that the *relative* total transmitting power consumption is reduced when the network topology changes from single-hop to multi-hop. For an α of 2 which is the adopted value in this study, the power consumption is 100% (i.e. maximum value) for single-hop topology, while it is about 11% with h is equal to 9.

Now we continue with the analysis by not just considering the transmit power but also the receive power at every node.

$$P_T = \sum_n P_{tx}(n) + \sum_n P_{rx}(n) \quad (3.5)$$

where, $P_{tx}(n)$ is the total transmit power, $P_{rx}(n)$ is the total receive power, and n is the number of active nodes.

We can assume that the total receiving power for each node is a constant as the receiver circuitry uses relatively constant power to amplify the received signal. For example, if we assume $P_{rx}(n)$ is 10% of the maximum power that is consumed in a single-path topology, the estimated total power consumption (P_T) for all possible case studies can be compared against Equation 3.4 as shown in Figure 3.7.

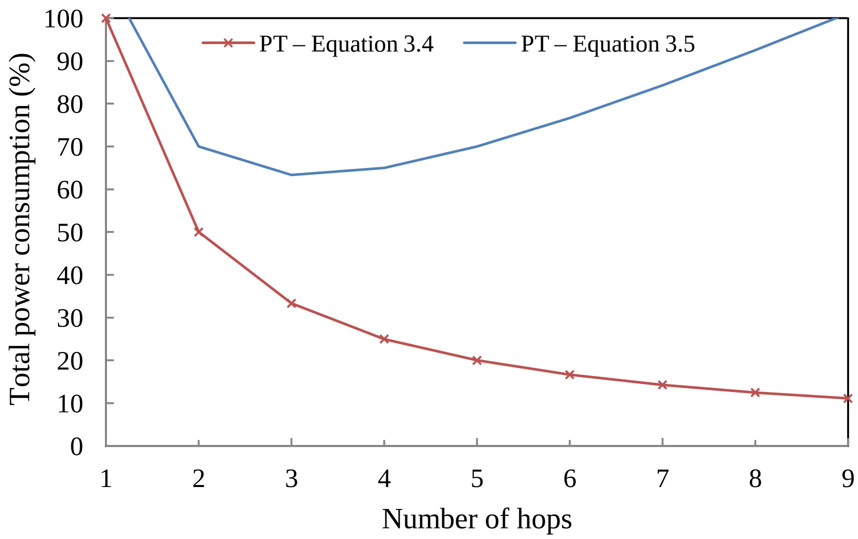

Figure 3.7 Total power consumption percentages for α=2.

Figure 3.7 clearly shows that the total power consumption predicted by the developed equation is higher than that of Equation 3.4. For example, at a 2-hop topology, the total power consumption is 70% when considering the transmitter and the receiver, while it is about 50% when only the transmitter is taken into account.

Also, the figure shows that increasing the number of hops more than three leads to an increase in the power consumption in the developed model in contrast with that of Equation 3.4. Hence, given the above assumptions it is clear that best results are obtained when the path is broken up between 2 and 8 hops.

3.4 Throughput neutrality in a WSN

In this section, we look at different case studies of different network topologies and study the effect of multiple hops and multiple paths on throughput. The assumption here is that each sensor node has a simple omni-directional antenna with a free space propagation model and can only either receive or transmit and cannot do both at the same time and if it is being interfered with, we assume the worst case scenario and assume that packets cannot be received. Although, we are aware in real receiver systems that a receiver may still receive even when being interfered with under a condition known as capture [37].

In Figure 3.8, we consider Case 13, for a single-hop/single-path topology, Node S sends 4 packets in 4*t* timeslots, the throughput *T* is equal to 4/4 =1. The total number of timeslots to deliver all packets is t_T, the number of packets is *N*, and we assumed that every packet takes one timeslot. Hence, the throughput for this case is simply:

$$\text{Throughput, } T = \frac{N}{t_T} \qquad (3.6)$$

where, t_T is the total number of timeslots to deliver all packets and *N* is the number of packets. In Figure 3.8, we consider the case of 2 hops with a single-path. In Case 14, Node S transmits data to Node D through an intermediate node (Node 1). The data will be duplicated through retransmission and hence the resulting throughput will be halved. For instance, when Node S sends 4 packets to Node D, it needs 8 timeslots,

and (T = 4/8 =0.5). When each packet needs two time slots ($2t$) and t equal to 1 while we assumed that every packet takes one timeslot,

$$t_T = 2N \tag{3.7}$$

We formulate the two-hop case for a single-path topology as,

$$T_{Single\text{-}path(2\text{-}hop)} = \frac{N}{2N} = 0.5 \tag{3.8}$$

Now, we consider the 2, 3 and 4 independent path cases. In Cases 15, 16 and 17, for two hops at two, three or four paths respectively, Node S sends 4 packets in 5 timeslots, the throughput is equal to T = 4/5 = 0.8. When Node S sends data through two hops the throughput is not reduced by the same amount as in Cases 13 and 14 this is due to the number of parallel paths. In the same way, we also formulate the two-hop case for multiple paths topology. Hence, When t=1 timeslot, the total number of time slots is,

$$t_T = t\,(N+1) = N + 1 \tag{3.9}$$

$$T_{Multi\text{-}path/2\text{-}hop} = \frac{N}{N+1} \tag{3.10}$$

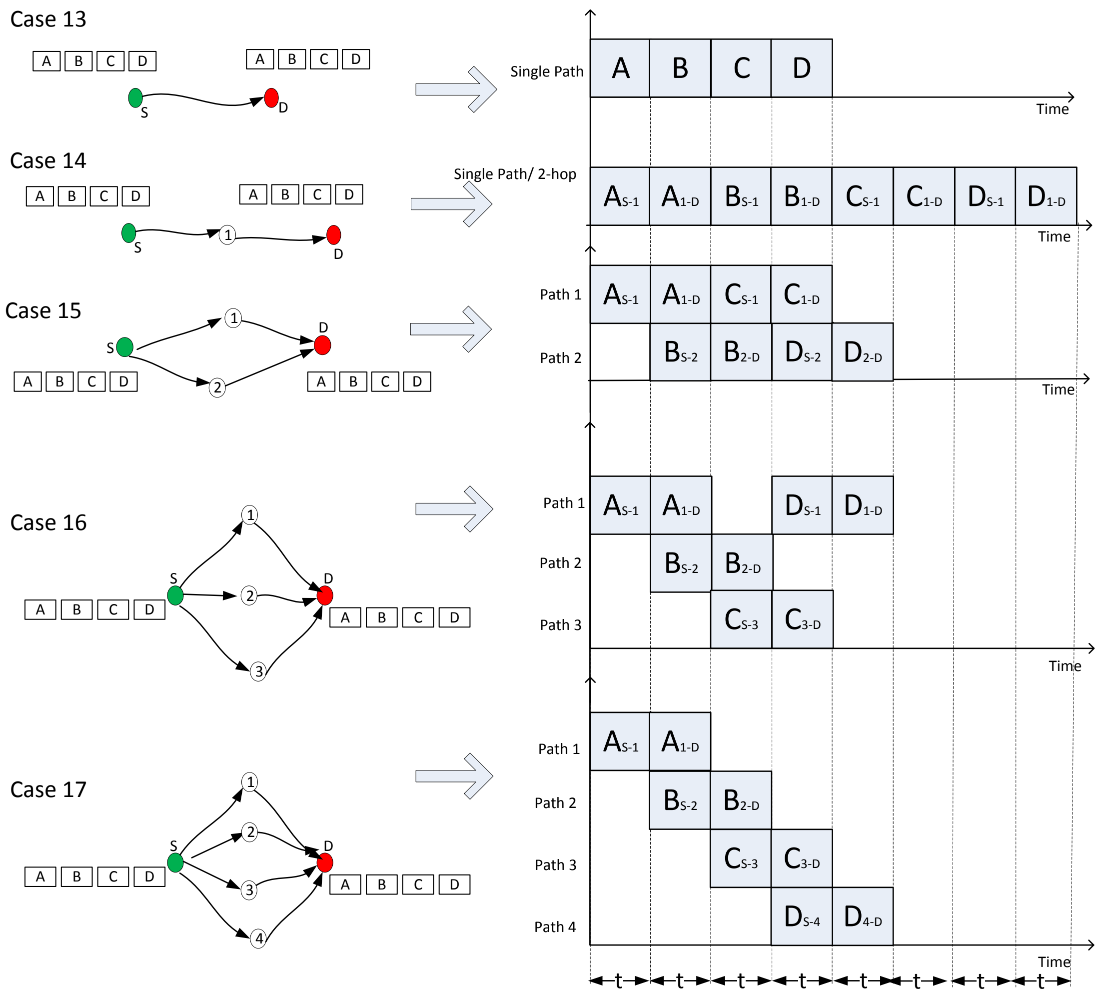

Figure 3.8 Single-path with multiple (2, 3 and 4) paths comparison.

It is important to note here that there was no increase in throughput when the number of paths was increased from 2 to 4. This is due to the fact that the bottle neck is at the transmitter and receiver where packets will converge and they will have to wait as the receiver cannot receive multiple packets at the same time. However, if we have the case of multi-channel/multi-transceiver then, there will be a significant increase in the throughput. Assuming we have 3 radios in each node then, all packets can be transmitted simultaneously and received at the receiver simultaneously [114]. But we continue with the assumption of a simple radio as this is the worst case scenario and has cost advantages for simple wireless sensor networks.

Now, we move on to the cases where we have 3 hops to traverse. Figure 3.9 shows the case studies for 3 hops. Case 18 shows a 3-hop topology with a single-path, Node S sends data to Node D through the other two intermediate nodes between them (Nodes 1 and 2). The resulting throughput is less than half as 9 slots are required to transmit 4 packets, we can determine a more general equation for the throughput and notice it converges to 0.5 if a large number of packets is transmitted. Hence,

$$t_T = t\ (2N+1) = 2N+1 \tag{3.11}$$

$$T_{Single\text{-}path/3\text{-}hop} = \frac{N}{2N+1} \tag{3.12}$$

Cases 19 and 20 show that cases where there are 3 hops with 2 and 3 parallel paths respectively. Node S sends 4 packets in 6 timeslots, the throughput is equal to T = 4/6 = 0.75. And this is the same result as when the number of paths is increased further to 3. Hence,

$$t_T = t\ (N+2) = N+2 \tag{3.13}$$

$$T_{Multi\text{-}path/3\text{-}hop} = \frac{N}{N+2} \tag{3.14}$$

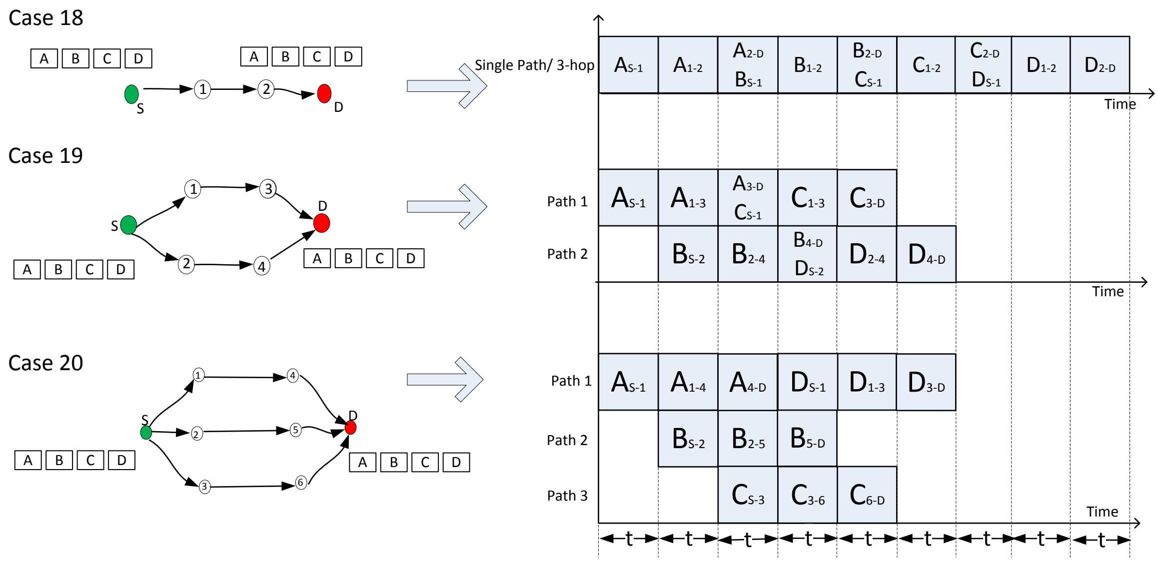

Figure 3.9 Three-hop with single-path and multiple path comparison.

Hence, the formula shows that the throughput will converge to 1 as the number of packets sent approaches infinity.

Now considering more than 3 hops, Figure 3.10 shows different case studies where 4 hops are available for single and multiple paths. Case 21, shows 4-hops with a single-path, Node S sends data to Node D through the other three intermediate nodes between them (Nodes 1, 2 and 3). When Node S sends 4 packets to Node D, it needs 10 timeslots, and hence the throughput is T = 4/10 =0.4. We formulate 4-hop for a single-path connection as,

$$t_T = t\,(2N+2) = 2N+2 \tag{3.15}$$

$$T_{Single\text{-}path/4\text{-}hop} = \frac{N}{2N+2} \tag{3.16}$$

Again, note that the throughput will converge to 0.5 in the case of many packets being transmitted.

In Cases 22 and 23, for 4-hop at two and three paths respectively, Node S sends 4 packets at 7 timeslots in all cases, the throughput is equal to T = 4/7 = 0.57. Notice that no increase in throughput is attained when the number of independent paths is

increased from 2 to 3 paths. We formulate the four-hop case for multiple path topologies as follows.

$$t_T = t\,(N+3) = N+3 \qquad (3.17)$$

$$T_{Multi\text{-}path/4\text{-}hop} = \frac{N}{N+3} \qquad (3.18)$$

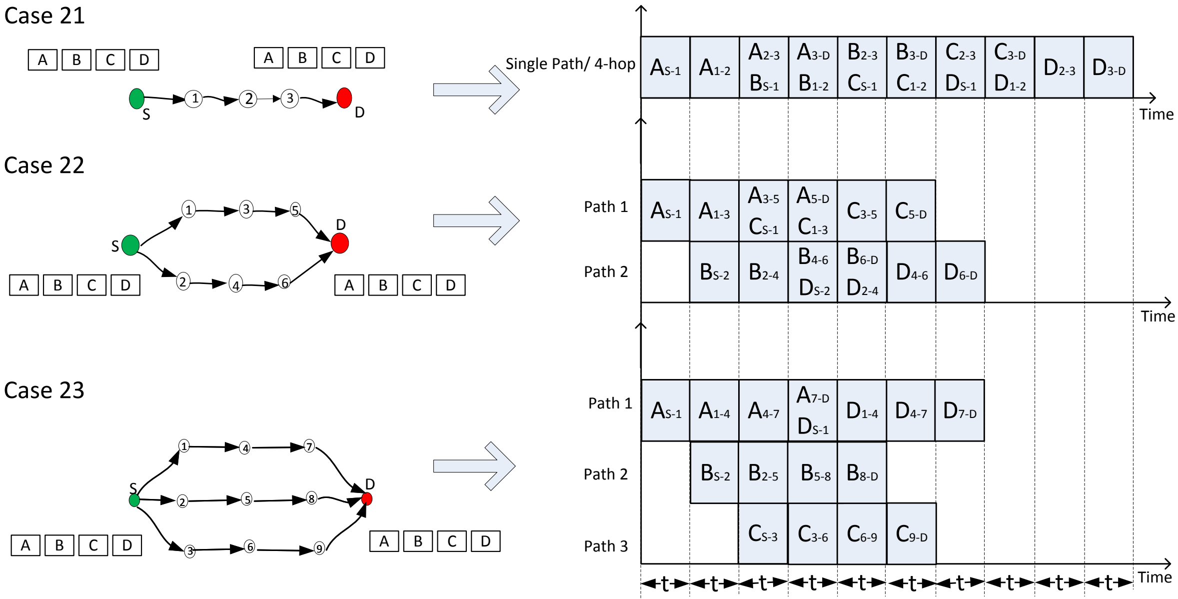

Figure 3.10 Four-hop with single-path and multiple path comparison.

Please note that, for 2 and 3 parallel paths all have similar throughputs due to the fact that the bottle neck are at the transmitter and receiver where packets converge and they will have to wait as the receiver cannot receive multiple packets at the same time. And it clear that the throughput is inversely proportional to the number of hops and not the number of paths in multi-path topology.

If we assume that h is the number of hops, we can formulate a general equation for the single-path/multi-hop case based on Equations 3.8, 3.12 and 3.16.

$$T_{Single\text{-}path} = \frac{N}{2N+(h-2)} \qquad (3.19)$$

where, $T_{Single\text{-}path}$ is the throughput for the single-path/multi-hop network topologies, N is the number of packets, and h is the number of hops while ($h \geq 2$).

In the same way, we derive the throughput equation for multi-path/multi-hop case based on Equations 3.10, 3.14 and 3.18:

$$T_{Multi\text{-}path} = \frac{N}{N+(h-1)} \tag{3.20}$$

where, $T_{multi\text{-}path}$ is the throughput for the multi-path/multi-hop network topologies, N is the number of packets, and h is the number of hops while ($h \geq 2$).

Taking a closer look at Equations 3.19 and 3.20, and taking the limits as N goes to infinity, one can readily deduce that the throughput for the single-path will converge to 0.5 regardless of the number of hops (as shown in Figure 3.11). For the multi-path case, as shown in Figure 3.12, it can also be readily deduced that the throughput will converge to 1 as long as there is at least one extra path available from the main path. Adding more than one path will result in a similar outcome (convergence to 1) but with a slower convergence rate,

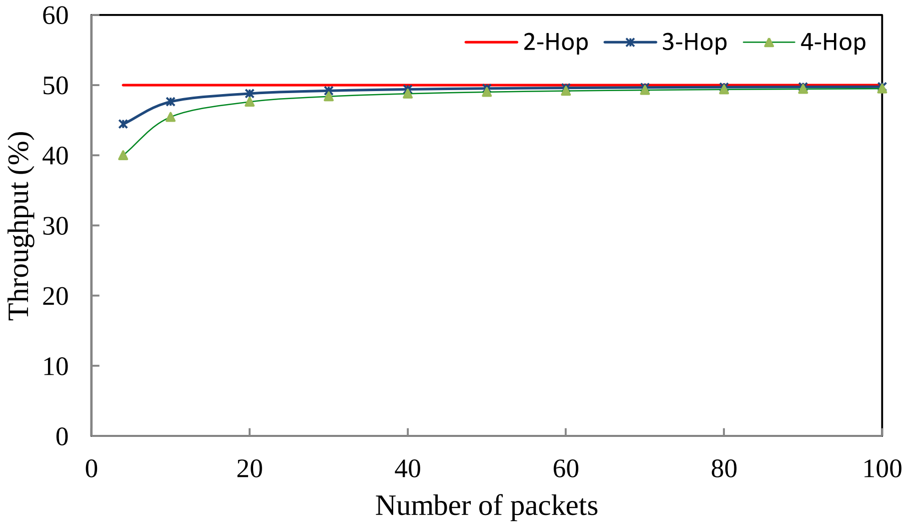

Figure 3.11 Single-path throughput comparisons.

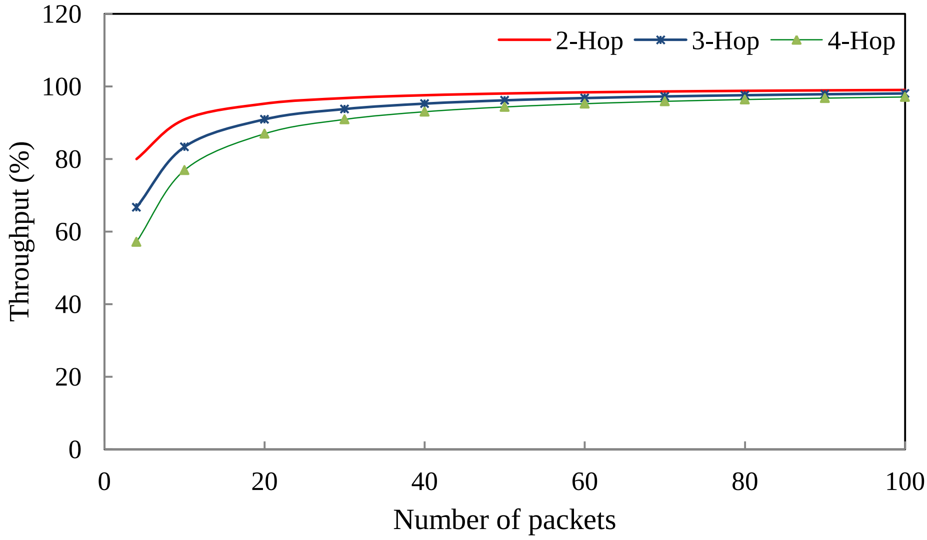

Figure 3.12 Multiple paths (2 or more paths) throughput comparison.

Hence to reach our goal of throughput neutrality, we need to discover at least 2 independent paths and not more. As having more independent paths, does not result in any increase in the end-to-end throughput. The two independent parallel paths created compensates for the reduction in throughput due to more hops, (the number of hops has a very low effect for the throughput while N goes to infinity). The assumption here is that end-to-end flow control works perfectly.

3.5 Conclusions

Increasing the number of hops in a multi-hop sensor network will reduce the throughput by a factor of N if no end-to-end flow control is used and this is the case for at least 2 hops. This is because of the store and forward techniques that are used by the sensor nodes. To solve such a problem, a multi-path topology has been proposed in order to keep throughput and loss neutral. The proposed solution can be achieved by combining these two insights (i.e. multi-hop and multi-path) in one algorithm. For this reason, the proposed algorithm needs to involve both efficient TPC to find the optimal transmission power, and the multi-path routing protocol

needs to maintain throughput across at least two independent paths. From a power perspective, Figure 3.7 shows that the optimal number of hops is 3-hops for each path. Moreover, the number of hops must be between 2 and 8 ($2 \leq h \leq 8$). In other words, throughput neutrality is maintained while the two-paths are utilised, and the number of packets goes to infinity (i.e. N = 1000 packets) and breaking one long transmission into 3 hops should theoretically result in an overall power saving for the network. It is also clear from Figure 3.12 that the throughput is maintained when using two independent parallel paths and no increase is obtained if more than two paths are used, this is due to the limitation of the single radio channel. As different packets converge from different paths to a single receiver, effectively all will have to wait to be received one at a time. In the next chapter, we propose combining TPC and a multi-path routing protocol in order to increase the life time of the sensor network but also maintain the original throughput and hence achieve a net advantage.

CHAPTER 4: TPC PROTOCOL FOR HIGH DENSITY WSNS

4.1 Preliminaries

Based on the conclusions made in Chapter 3, this chapter presents a new protocol that combines multi-path routing as well as Transmit Power Control (TPC) for high density Wireless Sensor Networks (WSNs). The Chapter begins by discussing TPC then describes the multi-path protocol chosen in more detail. The Chapter ends by describing the new modified TPC protocol.

4.2 Combination of multi-hop and multi-path topologies

In Chapter 3, it was concluded that two paths are sufficient in order to maintain throughput and any additional paths did not increase the overall throughout between a source and a destination. The reason for this being that the radio on each node can only receive or transmit only to a single source or destination, hence the bottleneck. In Chapter 3, it was also shown that an energy saving is obtained when a single long range transmission is broken down into 3 or 4 hops, hence taking advantage of the inverse power rule of propagation. In this Chapter, we will combine these two findings and present a practical algorithm that discovers two paths and breaks any single long range transmissions into three or four hops if possible and hence obtain the benefits of energy saving without the loss of throughout.

Based on the findings of Chapter 3, it was shown that the optimal number of hops is three hops for each path. But an energy saving can also be obtained if the number of hops is between 2 and 8 ($2 \leq h \leq 8$). It was also shown that the neutral results of throughput are obtained when we use two independent parallel paths and no increase is obtained if we use more than 2 paths, this is due to the limitation of the single radio channel as mentioned above. In other words, throughput is maintained while the two-path are utilised, and the number of packets (N) goes to infinity. To achieve

our aim, a suitable TPC protocol and an appropriate multi-path routing protocol have to be selected based on the reviewed literature, and considering the pros and cons of the chosen protocols, afterword, we find a method to combine the selected protocols in order to develop the proposed algorithm.

4.3 TPC protocol

Several methods were proposed to enhance energy efficiency for WSNs such as power control in the MAC layer, topology control, efficient data transmission and efficient routing protocols. This section dwells on transmit power control protocols that are used to minimise energy consumption and avoid interference in the network.

A TPC protocol selects the transmission power level dynamically based on many factors (features) such as network topology [35], distance between the nodes [25, 45, 53, 63], signal strength [37, 48], capacity or gain of the wireless channel [34, 43], link quality [41, 46, 56, 59], residual energy at the nodes' battery [51] and network interference level [27].

In order to obtain energy saving, a long range transmission can to be broken up into shorter transmissions. In dense WSNs, we can expect multi-hopping to consume a lesser amount energy than single-hopping while using the minimum required transmission power to maintain the connectivity between the transmitter-receiver pairs. This procedure can enhance the energy efficiency and extend the nodes' lifetime within WSNs [53].

Zhao et al. [35] uses a network topology that is self-organising and a multi-hop topology to reduce power consumption. However, the residual energy depletion can be increased by the use of a multi-hopping in stationary nodes such as the sink. The residual energy of the sink can be depleted rapidly as a result of their regular transmitting of data to other nodes.

The distance between transmitter and receiver pair can also be used to adapt the transmitting power. In [25], multi-hopping was adopted to minimise power consumption based on the number of hops and network density. Similarly, Cheng *et al.* [53] and Zhu [63] propose a TPC protocol for multi-hop WSNs; the power level can be adjusted based on the distance between nodes in a free space path loss model. However, the network density is not considered by [25, 53, 63].

The chosen TPC protocol is a modified version of the one proposed by Meghji *et al.* [12, 13, 54, 55]. The protocol relies on adjusting the transmit power into 8 set levels based on IEEE 802.15.4 WSNs. The transmission power can be easily adjusted based on nodes' residual energy and signal strength. Additionally, the power function of the distance (d) between any transmitter-receiver pair can be calculated based on the radio channel fading. The channel fading is generated when the electromagnetic signals are moved through two different paths, and the addition and subtraction of the signals at multiple points results in multi-path fading. There are two possible ways to setup a path between any two nodes: 1. A line of sight or direct path or 2. An indirect reflected path [115]. The multi-path fading can help to calculate the cross-over distance ($d_{x\text{-}over}$) which is the distance between two transceivers that can receive and transmit to one another. This is affected by three factors: the transmitter and receiver antenna height as well as the signal wavelength as shown in Figure 4.1.

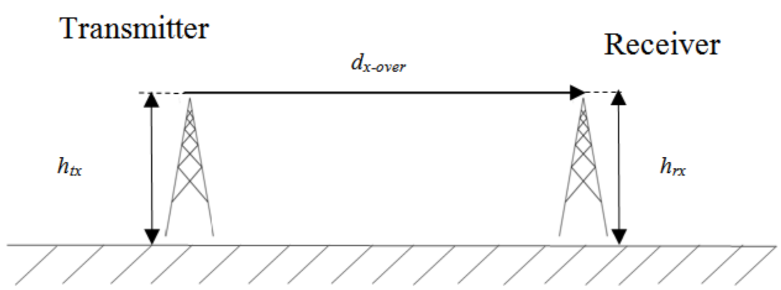

Figure 4.1 The distance between transmitter and receiver.

The free space model was used for the direct-path, and the multi-path fading model was used for the reflected-path based on $d_{x\text{-}over}$ which can be calculated by Equation 4.1.

$$d_{x\text{-}over} = \frac{4\pi\, h_{tx}\, h_{rx}}{\lambda} \qquad (4.1)$$

where, $d_{x\text{-}over}$ is the cross-over distance, h_{rx} is the transmitting antenna height, h_{tx} is the receiving antenna height, and λ is the carrier signal wavelength.

The conditions for selecting the antenna model are:

- If $d < d_{x\text{-}over}$ then the utilised model is a free space model.
- If $d > d_{x\text{-}over}$ then the utilised model is a two-ray ground propagation model.

d in this case can be calculated in different ways. In fact different studies have used different methods of estimating d. These include Link Quality Indicators (LQI) [48], Global Positioning System (GPS) [76] or Received Signal Strength Indication (RSSI) [46]. Here, we assumed that the nodes are deployed as a grid in specific area for geometric field and hence the distance d is known and can be calculated by using GPS upon deployment. Hence, we can use the following equations to find the received signal power as a function of d to predict the cross over distance between the transmitter-receiver pair for both free space and two-ray ground propagation models in a WiFi system.

$$P_{rx}(d)_{\text{Free space model}} = \frac{P_{tx}\, G_{tx}\, G_{rx}\, \lambda^2}{(2\pi)^2 d^2\, L} \qquad (4.2)$$

$$P_{rx}(d)_{\text{two-ray model}} = \frac{P_{tx}\, G_{tx}\, G_{rx}\, {h_{tx}}^2\, {h_{rx}}^2}{d^4\, L} \qquad (4.3)$$

where, G_{tx} is the gain of the transmitter antenna, G_{rx} is the gain of receiver antenna, and L is the system loss factor with a value of equal or greater than one. In order to

simplify Equations 4.2 and 4.3, the assumptions of Meghji *et al.* [12, 13, 54, 55] are used:

- $G_{tx} = G_{rx} = 1$ for omni-directional antenna,
- $h_{rx} = h_{tx} = 1$ meter,
- $L = 1$ without any loss,
- $\lambda = \frac{3\times10^8}{2.45\times10^9}$ for wireless frequency 2.45 GHz and the light wavelength equals 3×10^8,
- $d_{x\text{-}over}$ is approximately equal 103 meter.

Equations 4.2 and 4.3 can be re-written in the following form.

$$P_{rx}(d)_{\ Free\ space\ model} = \frac{P_{tx}}{d^2} \qquad if\ \ d < 103 \tag{4.4}$$

$$P_{rx}(d)_{\ Two\text{-}ray\ model} = 9.4949\times10^{-5}\ \frac{P_{tx}}{d^2} \qquad if\ \ d > 103 \tag{4.5}$$

Hence, the transmission power for each packet can be estimated from the Equations 4.4 and 4.5. In the proposed TPC algorithm, a similar procedure can be used when using different parameters such as the free space propagation model and the IEEE 802.11g radio channel.

For the purpose of this work, we have developed a TPC protocol similar to Meghji et al. [12, 13, 54, 55] for the following reasons:

1. The proposed TPC is reasonably accurate and depends on antennas gain, wavelength, antennas height and the system loss factor [55]. We can adopt these features for IEEE 802.15.4 and IEEE 802.11 with similar assumptions as they operate in 2.4 GHz and both employ spread spectrum techniques. We assume that each node has an omni-directional antenna, and the frequency 2.45 GHz is similar for both standards.

2. According to the proposed conditions above (If $d < d_{x\text{-}over}$ then the utilised model is a free space model), this study assumed that the nodes are deployed with a high density to enable multi-hopping communication which needs *d* to be less than 100 or so meters. That means based on Equation 4.4, in most cases we can use the free space model.

4.4 Multi-path routing protocol

While cutting down the transmission range is good for saving energy. It has the opposite effect on throughput and hence a reduction in throughput is obtained when the same packet is retransmitted multiple times. Hence, multiple paths need to be used in order to compensate for this effect. For single-channel/single-transceiver WSNs, the overall network throughput and channel capacity are limited. This is due to the fact that the bottleneck is at the transmitter and receiver where packets will converge and they will have to wait as the receiver cannot receive multiple packets at the same time.

Several routing protocols have been proposed for WSNs and we have discussed the relevant works in Chapter 2. An added benefit of multiple routes is balancing the load on the different nodes. Frequent use of the shortest path increases the rate of energy use at each active node in single-path WSNs. However, multi-path routing protocols are utilised to establish a sufficient number of paths as it balances data traffic load. Enhanced balancing of the data traffic load over a multi-path WSN can extend the network's lifetime.

Hence, before proposing any improvements or suggestions for a new routing protocol, we propose examining an existing multi-path routing protocol under the mentioned case studies in Chapter 3. LBMRDSR [113] was proposed as a load balancing multi-path routing protocol based on single-path DSR to solve the network

congestion problem [113]. In [105], Multi-path AOMDV-inspired protocol was developed based on AODV protocol, it updates the routing protocol of each node periodically to minimise the data latency. Data reliability and node or link failure were not considered in both protocols. Also, AOMDV is classified an inefficient routing protocol due to the high power consumption through the multi-path route establishment process, [105, 113].

After careful consideration, we decided to further investigate Multi-path Optimised Link State Routing (MP-OLSR) protocol [98, 111, 112] as a candidate multi-path protocol. It can be defined as a hybrid multi-path routing protocol that uses proactive discovery in the adjacent area of the sensor node, while using reactive protocols to communicate across the nodes. MP-OLSR is designed based on the single-path OLSR protocol. Both protocols utilise similar processes in the detection of adjacent nodes and network topology, but utilise different data packet routing schemes. Within OLSR, the source node computes the shortest path to the destination and relays the data packets to the next-hop adjacent node. The intermediate nodes relay the data packets based on their routing table. Within the MP-OLSR, the source node computes multi-path, and balance its data packets over the established paths.

4.4.1 Optimised Link State Routing (OLSR)

OLSR (RFC 3626) proactive routing protocol was proposed by Clausen *et al.* [96, 97]. The OLSR protocol has a stable link because of its proactive nature that builds up the on-demand routes instantly. OLSR minimises the number of accumulated control messages by allocating some nodes such as the multipoint relays (MPRs) which are able to broadcast their control messages through the specific area from the network. Furthermore, it communicates only with a subset of adjacent nodes known

as their MPR selectors. This method minimises the amount of retransmitted packets in the data-transmitting process. The OLSR protocol is optimised based on the below listed functions:

1. Multipoint relay: OLSR utilises MPR as the relay of the *Topology Control* (*TC*) messages to limit the broadcasting of unnecessary messages. Any source node identifies their MPRs from the "1-hop neighbour" node by the *HELLO* messages. After that, the allocated MPRs identify its "2-hop neighbour" nodes. Each MPR must thereby communicate to the entire network regarding their own set of MPR selectors by broadcasting *TC* messages. *TC* message contains all the information about the selected MPRs. Then, the retrieved data can be stored in the topology set. Each entry within these sets is inclusive of data relevant to the address of the MPR which is identified as the last-hop, and the MPR selector will be marked as a node. Figure 4.2 shows the flooding of control messages with and without MPRs.

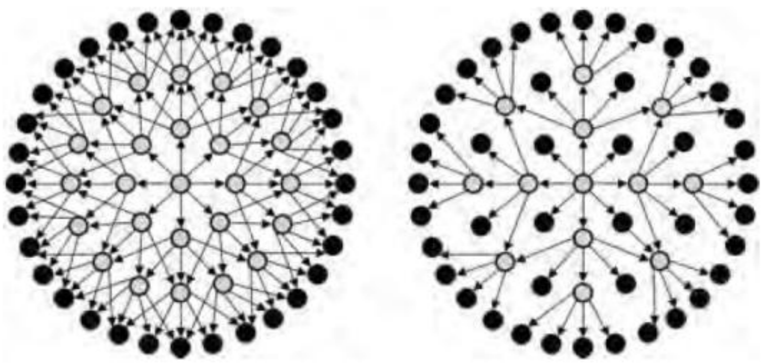

Figure 4.2 Broadcasting messages with MPR (left) and without MPR (right) [98].

2. Neighbour sensing: every node in the network floods *HELLO* messages periodically regarding their adjacent nodes' status. These *HELLO* messages address the "1-hop neighbour" and then they allow for each node to attach the information of their "2-hop neighbour" node set.

3. Routing table creation: every node in the network retains and updates its routing table that includes information and details of the deployed nodes. Considering that, the routing table is created and maintained based on both the topology set table and the neighbour set table.
4. Link state advertisement: every node in the network retains the link state by flooding *TC* and *HELLO* messages regularly in order to update the network topology information. The network topology information includes link-state which is called a "1-hop neighbour", and 2-neighbour set which is identified as a "2-hop neighbour" as well as the topology-set based on MPRs and MPR selectors.

4.4.2 Multi-path Optimised Link State Routing protocol (MP-OLSR)

The MP-OLSR protocol [98, 111, 112] is a hybrid multi-path routing protocol that merges the proactive and reactive properties. MP-OLSR floods *TC* and *HELLO* messages for each adjacent node to update the topology of the wireless network. However, MP-OLSR does not retain a routing table that collects the routing information for a long-term. It identifies the needed paths when the data packets are required to be sent. The MP-OLSR process includes two mechanisms, topology sensing and route computation.

1. Topology sensing: this function involves forcing the nodes to obtain the topology information of the network that includes link-state, neighbour-set detection and topology-set discovery. The function utilises the MPRs benefits based on single-path OLSR.
2. Routes computation: this function utilises the multi-path Dijkstra algorithm to tabulate the multi-path routing by using the information of the topology

sensing. The primary-path information is attached to the header of the data packets. The intermediary nodes read the packet header and then deliver the packet to the next-hop adjacent node.

In addition, the recovery-path is established to overcome the challenges of maintaining the primary and secondary paths. Despite this, the MP-OLSR doesn’t always maintain a routing table for each possible destination in the network as it only addresses the multiple paths when data packets require to be communicated within the network.

For the purpose of this work we have proposed modifying MP-OLSR for the following reasons:

1. MP-OLSR is a hybrid routing protocol which can switch from proactive to reactive behaviour, the trade-off between proactive and reactive features provide high resilience that gives the best of both worlds;
2. MP-OLSR uses multi-path *Dijkstra* algorithm that deals with both low and high density networks;
3. MP-OLSR is suitable for low-cost sensor nodes such as it does not need to keep and maintain routing table which overburdens the memory of the sensor nodes;
4. MP-OLSR attaches all the required routing information at the header of data packet, which can help to append the TPC events inside this header to obtain efficient routing;
5. MP-OLSR considers network reliability and fault tolerance which were not taken into account in most of multi-path routing protocols;
6. MP-OLSR protocol structure can be developed by modifying QualNet 5.1 source codes.

4.5 The proposed TPC protocol for high density WSNs

In this section, we develop a combined MP-OLSR with TPC. We also limit the number of paths and number of hops in accordance of the previous chapter's observation to obtain overall energy saving in the network but maintaining throughput at the same time.

The focus of this work is to minimise energy use while keeping throughput neutral. Based on the observations in Chapter 3 and power loss due to the inverse square law, reducing the range and hence transmit power through an appropriate TPC is required. There must be enough paths to mitigate the throughput reduction due to multi-hoping. As mentioned in Chapter 3, using two paths with a minimum number of hops may offer possible solution to maintain throughput. So, the TPC for high density WSNs protocol is proposed to combine multi-path routing protocol and TPC for dense WSNs in order to maintain throughput and constrain energy at the same time.

In this section, we develop a TPC WSN protocol based on both a TPC protocol that adopted by Meghji *et al.* [12, 13, 54, 55] and the MP-OLSR protocol [98, 111, 112] as a multi-path routing protocol. The protocol has three stages: In the first stage, the source node discovers and establishes the primary-path and non-interfered secondary-path which is the minimum required number of paths. In this stage, the developed protocol utilises MP-OLSR (as described in Section 4.4) to discover and establish two non-interfered parallel paths (Steps 1 and 2, as shown in Algorithm 4.1). In the second stage, the adjustment of the transmitting power is based on the computation of the distance ratio (d) and the path loss exponent (α) is utilised similar to that in [12, 13, 54, 55] (as described in Section 4.3). The source node calculates the distance to the next-hop adjacent node, and divides this value by the maximum possible distance which is 120m for WiFi systems (as mentioned in Chapter 3) to

find d, and it chooses the required transmit power level based on Equation 3.2 at α equal to 2 when utilising free space propagation model (Steps 3, 4, 5, 6 and 7, as shown in Algorithm 4.1). The final stage includes finding the optimal transmitting power dynamically by finding the optimal number of hops that are required to achieve high energy saving (Step 8, as shown in Algorithm 4.1). Algorithm 4.1 presents the proposed steps to enable TPC for high density WSNs. Also, Figure 4.3 presents the flow-diagram of the proposed algorithm.

Algorithm 4.1 TPC for high density WSNs.

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1. Establish first single-path route by using the multi-path routing protocol; *H_1*= number of hops in the primary-path; to reach the destination;
2. Discover non-interfered parallel path by using the modified MP-OLSR protocol; *H_2*= number of hops in the secondary-path; to reach the same destination;
3. *Hop_count*= Max(*H_1*, *H_2*);
4. *d*= 1/*Hop_count*;
5. Calculate P_{tx} based on Equation 3.2 [$P_{tx} = d^2 \times P_{tx\ (\mathrm{Max})}$];
6. For *i=0* to *Hop_count*, *i++*; {
7. Adapt P_{tx} (decrease) and include the adaptive P_{tx} level in *TC* message to next-hop adjacent node;
8. If [the *TC* message is timed out] Then [adapt P_{tx} (increase) and include the adaptive P_{tx} level in *TC* message to next-hop adjacent node]; go to 8; }
9. End

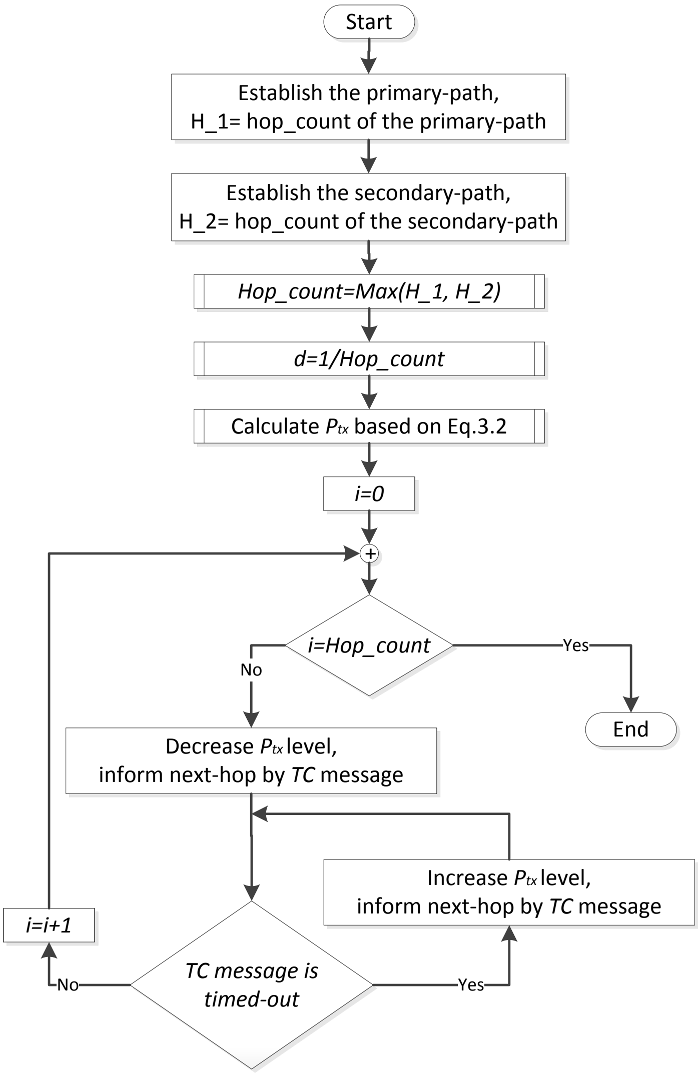

Figure 4.3 The developed TPC flowchart for high density WSNs.

Figure 4.3 simplifies the proposed algorithm steps. At first, the developed MP-OLSR routing protocol is utilised to establish primary and secondary paths. Then, hop-count metrics at each path (i.e. *H_1* and *H_2*) are calculated to compute how many hops are utilised. *Hop_count* can be used as a number of hops which is important variable to compute d as well as P_{tx} according to Equations 3.1 and 3.2.

$$d = \frac{1}{h} \tag{3.1}$$

where, d is the distance ratio, and h is the number of hops (*Hop_count*) where we assume that the total transmission range is split equally between hops.

$$P_n = d^{\alpha} \; P_{max} = \; d^2 \; = \; (\frac{1}{h})^2 \tag{3.2}$$

where P_{max} is 100% (or 1), and the path loss exponent (α) is equal to 2, assuming that the free space propagation model is used.

The transmitter node adapts its transmitting power, and attaches the calculated transmitting power level information at the header of the *TC* message which will be sent to the next-hop adjacent nodes. However, if this *TC* message times-out, the transmitter node increases the transmitting power level and repeats the previous step. If this *TC* message is delivered to the receiver node, the later uses this power level as a default transmitting power, and then sends its information to the next-hop adjacent node until reaching the destination node while considering the *TC* messages state (delivered or lost).

Here we give a more detailed description of the proposed TPC:

The source node assigns the next-hop adjacent node, if the next-hop adjacent node already existed in its "neighbour set" (i.e. 1's neighbour or 2's neighbour) then it transmits the control messages, if not, it rediscovers other nodes as next-hop adjacent nodes. Whenever, the source node discovers more than two next-hop adjacent nodes then it compares the distance to the discovered nodes, the nearest two nodes can be allocated as next-hop adjacent nodes in order to establish the required paths (two paths as mentioned in Chapter 3). After that, the source node adjusts its transmission range based on the allocated distance.

The intermediate node also allocates the next-hop adjacent node if the next-hop adjacent node already existed in its “neighbour set” then it forwards the control message, else, it rediscovers other nodes as a next-hop adjacent node in order to establish the required path. When the intermediate node discovered two or more next-hop adjacent nodes; it selects the nearest node. After that, the intermediate node adjusts its transmission range based on the allocated distance. This procedure is continued hop-by-hop to reach the destination node.

The proposed protocol can be summarised as shown in Figure 4.4 which present an example to describe the routing principle of TPC high density WSNs.

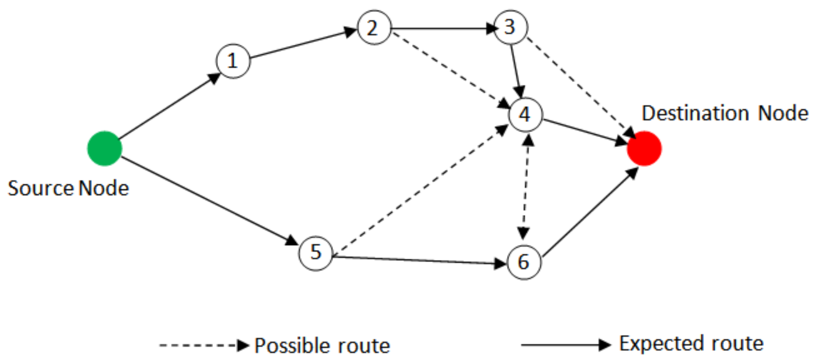

Figure 4.4 An example to explain the routing principle of the proposed protocol.

In Figure 4.4, when the source node attempts to transmit its data stream to the destination node, the required two paths can be selected based on the shortest distance between nodes. For example, the primary-path can be established by three possible routes:

$First\ route{:}Source \Rightarrow Node\ 1 \Rightarrow Node\ 2 \Rightarrow Node\ 3 \Rightarrow Destination,$

$Second\ route{:}Source \Rightarrow Node\ 1 \Rightarrow Node\ 2 \Rightarrow Node\ 4 \Rightarrow Destination,$

$Third\ route{:}Source \Rightarrow Node\ 1 \Rightarrow Node\ 2 \Rightarrow Node\ 3 \Rightarrow Node\ 4 \Rightarrow Destination,$

Based on the observations and assumptions in Chapter 3, the best possible route is the third route to establish the primary-path. Taking a closer look at Figure 4.4, the distance between (Node 2 and Node 3) is shorter than that between (Node 2 and Node 4) which means the expected link is shortest path (Nodes 2 and Node 3). Also, the other possible path is chosen between (Node 3 and Node 4), or (Node 3 and destination node), (Nodes 3 and Node 4) link is the most likely to be chosen due to the short distance in comparison to other link.

We limit the number of hops (as a maximum 8 hops only) to mitigate the increasing of the power consumption because of the receiver power consumption (as mentioned in Chapter 3). For that reason, the proposed protocol is optimised by selecting the lowest number of hops path instead of the shortest distance path.

4.6 Conclusions

In this chapter, we proposed combing a known TPC protocol and a well routing protocol to produce a new protocol that aims to reduce overall power use in a WSN while at the same time maintain throughput. A modified TPC from Meghji *et al.* [ref] was combined with the MP-OLSR protocol with modifications that resulted in the new protocol. In the next chapter, we will present the simulation results.

CHAPTER 5:TPC FOR HIGH DENSITY WSNS IN QUALNET

5.1 Preliminaries

In this chapter, we implement the proposed protocol in the QualNet simulation environment. The hypothesis of this thesis is that throughput can be maintained while the overall energy of the network can be reduced if this is the case. To test this hypothesis, we examine the simulation results of the proposed Transmit Power Control (TPC) for high density Wireless Sensor Networks (WSNs) based on the findings of Chapter 3 and Chapter 4. The simulation results are classified into two parts according to the pervious chapters, energy efficiency is the first part, and throughput neutrality in the second part. Then, we will simulate several scenarios to find the optimal topology.

5.2 Energy efficiency in a WSN

In dense WSN, increasing the number of hops can minimise the transmission power consumption by reducing the transmission range. We begin by first comparing the mathematical results obtained in Chapter 3, represented by Equations 3.4 and 3.5, these are repeated here for clarity. Firstly, we consider the simple model of the energy savings obtained by reducing the transmission range. The total power is given by the sum of the total transmission power of all nodes.

$$P_T = \sum_n P_n = \sum_n P_{tx}(n) \tag{3.4}$$

Then we consider the received power in the model. This is given in Equation 3.5 below.

$$P_T = \sum_n P_{tx}(n) + \sum_n P_{rx}(n) \tag{3.5}$$

where, P_T is the *relative* total power consumption, $P_{tx}(n)$ is the total transmit power, $P_{rx}(n)$ is the total receive power, and n is the number of active nodes.

We assumed that the total receive power for each node is a constant as the receiver circuitry uses relatively constant power to amplify the received signal. Note that, as mentioned in Chapter 3, the best results are obtained when the path is broken up between 2 and 8 hops. Also, a single-path topology gives similar results to a multi-path topology.

In this section, we will first begin by simulating a line network at certain distances as shown in Figure 5.1 for single-path/multi-hop topologies, then we will move on to test the multi-path scenarios based on Table 5.2 parameters in order to investigate the mathematical model that was mentioned in Chapter 3 (i.e. Equations 3.4 and 3.5). After that, we will discuss the power consumption for all case studies

Figure 5.1 shows the case studies that have been considered, simulated and repeated for various data traffic load to measure the residual energy at the battery, and to calculate the power consumption percentage for each active node.

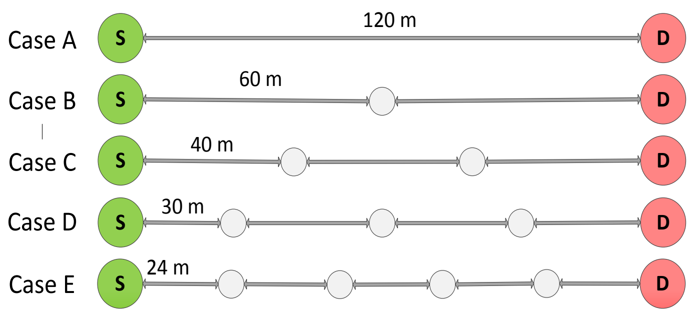

Figure 5.1 Multi-hop topologies.

Case A, Node S sends data to Node D by using a single-hop topology when the distance between them equals to 120m which is the maximum range of WiFi system. The source node transmits data at its maximum power to reach the destination node.

Case B implements a 2-hop path, and the distance hence equals to 60m by using one intermediate node to relay the data to Node D (i.e. mathematically halving the total power consumption as mentioned in Chapter 3). The reason this nominal simulation is conducted is to show the difference between the 'best case' scenario theoretical assumptions when tested against IEEE 802.11 MAC protocol that has sleep and idle modes when not transmitting. Also packets are needed for path establishment, and the discovery process. The network may also experience packet collisions and interference.

5.2.1 Single-path scenarios

To study single-path scenarios, the sensor nodes are deployed as a grid at (150×150) m^2 area in order to simulate the short distance among nodes. In this scenario, 30 sec is the simulation time for each scenario, and a Constant Bit Rate (CBR) application is used. The radio channel frequency is 2.4 GHz for IEEE 802.11g. The data packets are sent to reach the destination in several topologies (single and multiple hops topologies). With these configurations, the scenarios from Figure 5.1 are addressed. Table 5.1 shows the configuration of the simulation scenario for the proposed case studies.

Table 5.1 Parameters of multi-hop/single-path scenarios.

Parameter	**Configuration/ type/ settings**
Simulation tool	QualNet 5.1
Simulation Time	30s
Simulation area	(150×150) m
Type of Node	Sensor
Number of Nodes	9
Number of Hop (s)	Single, 2, 3, 4, 5, 6, 7 and 8
Applications	CBR
Application Packet Size	512 bytes
Transmission Interval	1
CBR Start time	1s
Routing Protocol	DSR
Number of Path(s)	Single
Mobility and Placement	None
Physical Layer Model PHY	802.11g
MAC Protocol IEEE	802.11
Packet Receptions Model	PHY802.11g
Wireless Channel Frequency	2.4 GHz
Transport Protocol	UDP
Network Protocol	IPv4
Transmission Power	Adjustable
Enable TPC in MAC layer	Yes
Battery Model	Linear Model

The simulation results are shown on the green line and labelled single-path. They show the power used as a percentage of the maximum single-hop case. The multi-hop single-path case is compared to the case where only the theoretical transmission power is considered (Equation 3.4) and a constant power model for the receiver is added (Equation 3.5).

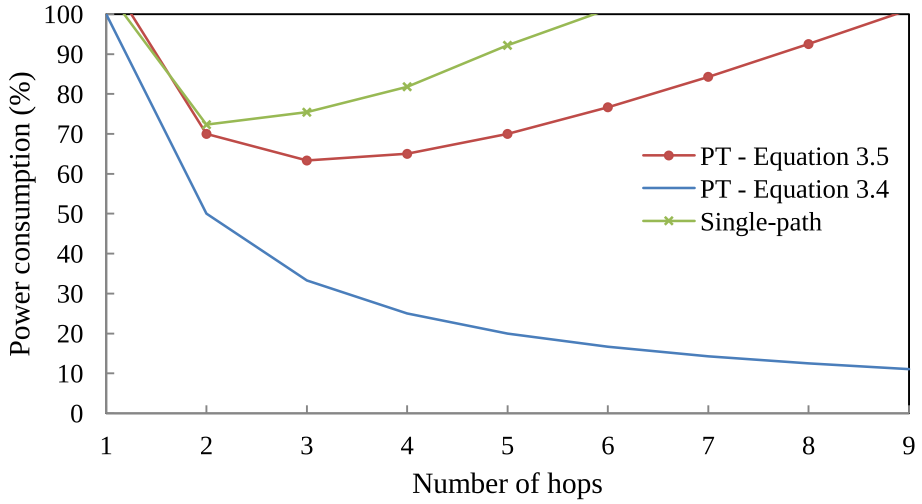

Figure 5.2 Total relative power consumption for single-path topologies.

Figure 5.2, shows that the theoretical results are optimistic when it comes to power saving and when the overheads of the MAC protocol are added, further power is used and the best savings obtained when the path is broken into 2 hops. Power savings are also achieved for 3, 4 and 5 hops due to adjusting the transmission range while the distance between nodes is reduced. However, using more than 5 hops consumes more power overall. Moreover, increasing the number of hops increases the overall power used through various factors including overhead messages, congestion, collision, interference, etc. More importantly, the graph shows that the simulated power consumption is higher than the mathematical model (Equations 3.4 and 3.5) owing to the not considered assumptions such as the consumed power in idle mode, sleeping mode, path establishment and discovery process.

5.2.2 Multi-path scenarios

A 2-path topology has been chosen to maintain throughput in the current study as it is explained in details in Chapter 3 and Chapter 4. The sensor nodes are deployed at (150×150) m^2 area in order to simulate the short distance among the nodes. In this scenario, 30 sec is the simulation time for each scenario, and a CBR application is used. As before, the radio channel frequency is 2.4 GHz for IEEE 802.11g. The data

packets are sent to reach the destination in several topologies (single and multiple hops topologies). Table 5.2 shows the configuration of the simulation scenario for the proposed case studies.

Table 5.2 Parameters of multi-path/multi-hop scenarios.

Parameter	**Configuration/ type/ settings**
Simulation tool	QualNet 5.1
Simulation Time	30s
Simulation area	(150×150) m
Type of Node	Sensor
Number of Nodes	16
Number of Hop (s)	2, 3, 4, 5, 6, 7 and 8
Applications	CBR
Application Packet Size	512 bytes
Transmission Interval	1
CBR Start time	1s
Routing Protocol	Multipath routing protocol
Number of Path(s)	Two
Mobility and Placement	None
Physical Layer Model PHY	802.11g
MAC Protocol IEEE	802.11
Packet Receptions Model	PHY802.11g
Wireless Channel Frequency	2.4 GHz
Transport Protocol	UDP
Network Protocol	IPv4
Transmission Power	Adjustable
Enable TPC in MAC layer	Yes
Battery Model	Linear Model

Figure 5.3 shows the total used power when 2 paths are used with 2 hops, 3 hops and so on. This is compared to the used power by the simulated single-path case and the theoretical results from equations 3.4 and 3.5.

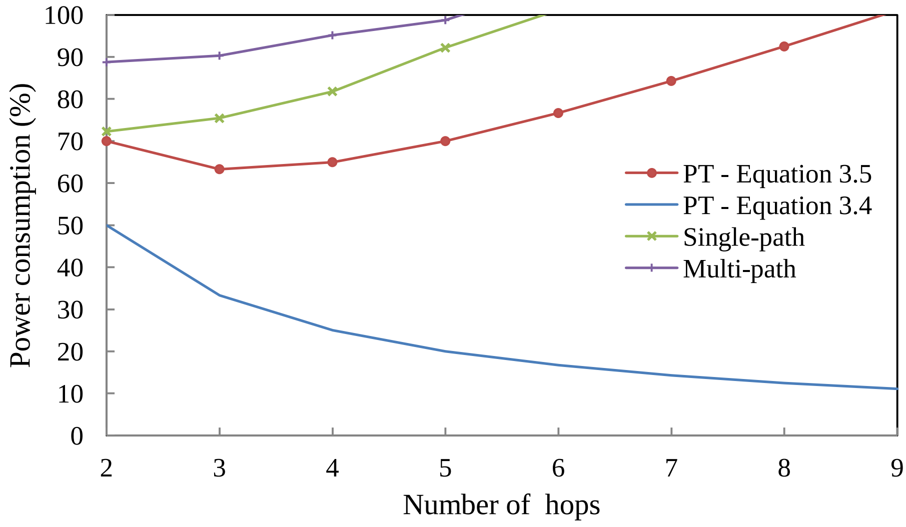

Figure 5.3 Total relative power consumption for two-path topologies.

Figure 5.3 shows that increasing the number of hops is accompanied with an increase in the total power consumption. The figure shows that if we have a 2-hop/2-path topology, this consumes 88% of the power of a single-hop topology to transmit the same amount of data. Note that, the reduction in power is nowhere near the 50% if assume the savings based on the inverse square rule of transmission. There are many reasons for this. This is due to the extra power requirement for the setup of an alternative path discovery and multi-path establishment processes. This figure also shows that increasing the number of hops leads to an increase in the power consumption in the multi-path scenario in contrast with the single-path scenario and Equation 3.5. Given the above results, a power saving is still obtained if the path is broken up between 2 and 5 hops.

In next section, we will move on to test the multi-path scenarios based on Table 5.3 parameters in order to investigate the mathematical model that was mentioned in Chapter 3 (i.e. Equations 3.20).

5.3 Throughput neutrality in a WSN

Here, we begin by first comparing the mathematical results obtained for multi-path case in Chapter 3, represented by Equations 3.20, this is repeated here for clarity.

$$T_{Multi\text{-}path} = \frac{N}{N+(h-1)} \tag{3.20}$$

where, $T_{multi\text{-}path}$ is the throughput for the multi-path/multi-hop network topologies, N is the number of packets, and h is the number of hops while ($h \geq 2$).

Note that, as mentioned above in Section 5.2, the best results are obtained when the path is broken up between 2 and 5 hops.

In this section, before simulating a large number of nodes, we first simulate topologies similar to those in Chapter 3 where the theoretical equations were developed. The purpose of this is to see how much additional overhead is added through setting up the routes and the MAC protocol. The topology setup is shown in Figure 5.4, where there are two paths between source and destination and 2 hops on each path. For the simulation, it was setup as follows: IEEE 802.11g radio channel sensor nodes are deployed as a grid in (150x150) m^2 area. 30 seconds is the simulation time for each scenario, and CBR applications are used to measure the end-to-end throughput at different data transmission rates. Table 5.3 shows the parameters of the simulation scenario for the proposed multi-path routing protocol with various network densities.

Table 5.3 Parameters of multi-path scenarios.

Parameter	Configuration/ type/ settings
Simulation Tool	QualNet 5.1 developed by C++
Simulation Time	30s
Simulation area	(150×150) m
Type of Node	Sensor
Number of Nodes	10
Number of Hops	2, 3, 4 and 5
Routing Protocol	Multi-Path routing
Number of Path(s)	Two
Attached Network	169.0.0.0 32
HELLO Interval	2s
TC Interval	5s
Refresh Timeout Interval	2s
Neighbour Hold Time	6s
Topology Hold Time	15s
Duplicate Hold Time	30s

Two-hop/multi-path scenario is implemented to examine the proposed mathematical model based on Equations 3.20) as it is described in Figure 5.4.

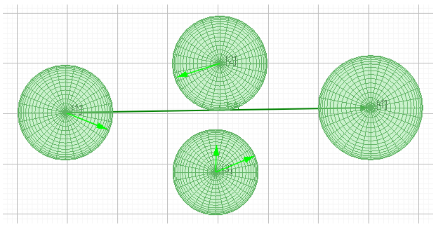

Figure 5.4 Two-hop/multi-path routing protocol.

In Figure 5.4, the source node is Node 1 and the destination node is Node 4. By using two-hop topology, there are two possible routes from source to destination which are:

$$First\ route \quad Node\ 1 \Rightarrow Node\ 2 \Rightarrow Node\ 4$$

$$Second\ route \quad Node\ 1 \Rightarrow Node\ 3 \Rightarrow Node\ 4$$

In the proposed multi-path, the data is relayed between the source and destination nodes through these two routes. The developed TPC is used as the multi-path routing protocol and the aggregated end-to-end throughput is compared to the mathematical model (i.e. Equations 3.20). Figure 5.5 shows the aggregated throughput for two-

hop/two-path topology. The simulation results are shown on the red line and labelled multi-path routing. They show End-to-end throughput as a percentage. The 2-hop multi-path case is compared to the case where only the theoretical throughput is considered (Equation 3.20).

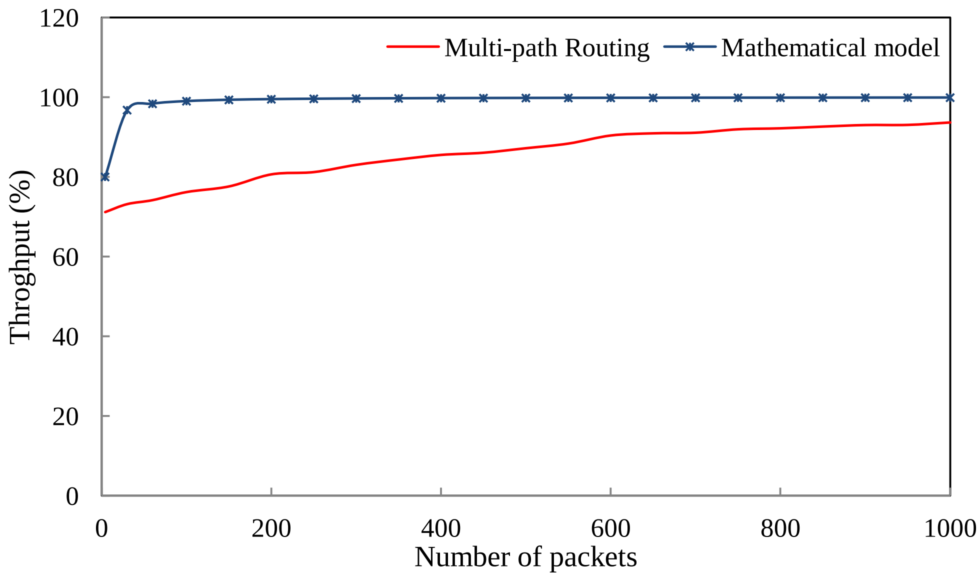

Figure 5.5 End-to-end throughput percentages for two-hop/multi-path scenarios.

Figure 5.5 shows that increasing the number of packets from 4 up to 1000 increases the end-to-end throughput from 71 to 99.9 percent for the case of multi-path protocol. These results are compared with the mathematically modelled results which are approximately 100 percent (i.e. neutral). The theoretical model is the best case scenario and does not consider any overheads, but as the simulation shows, there is a great load of overhead associated with setting up the path, and competing for the channel as well maintaining the route. Also, in the theoretical model, we assumed that one timeslot for each packet and equally sized packets as well as not considering the *TC*, *HELLO* and overhead messages, these results in a noticeable difference between the two routing cases.

Next, we examine three, four and five hops scenarios along the two separate paths to find the effects of using the developed TPC. Figure 5.6 shows that the aggregated throughput when the multi-path routing protocol is utilised with optimum number of hops.

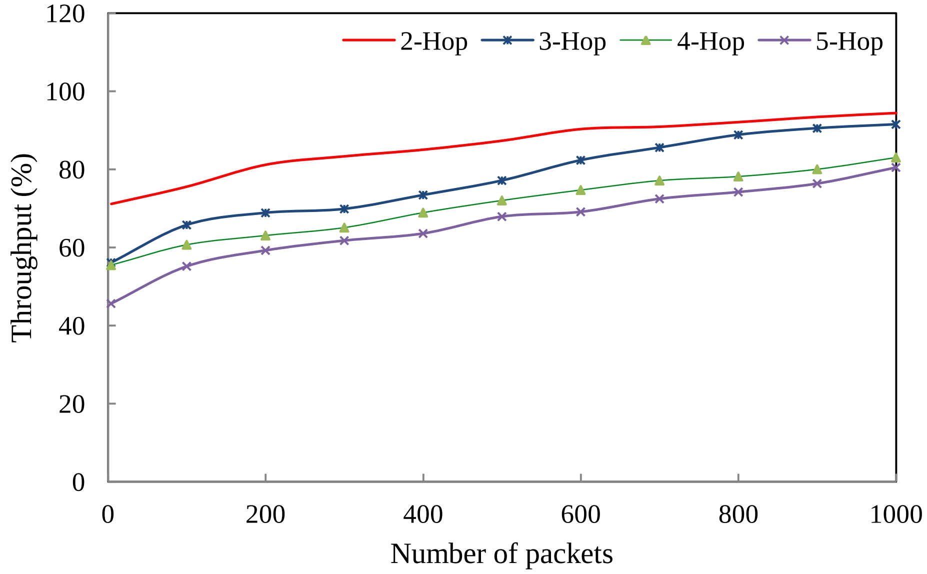

Figure 5.6 End-to-end throughput comparisons for multi-path routing protocol.

The total throughput is reduced when increasing the number of hops based on increasing the number of the required time for the data delivery progresses. For example, when the number of packets is increased up to 1000, the throughput percentage increases up to 94 and 92 percent for 2-hop and 3-hop topologies, respectively, while it increases up to 83 and 80 percent for 4-hop and 5-hop topologies, respectively. To conclude, the multi-path routing protocol can provide neutral throughput with a slower convergence rate which is one of the major targets of this study. Next, we will simulate several topologies to find the optimum results that are required to answer the research equations.

5.4 Network density

We derived a mathematical model (Chapter 3), and then, we simulated many scenarios to confirm the mathematical findings. The simulation results show that there is an energy saving by using multi-hoping and multi-path, but it's actually much less than anticipated when no overheads of the MAC and routing are considered. The throughput results show that throughput is higher when using two paths but it does not converge to the maximum very quickly as the theoretical model shows. This is again due to the routing and MAC overheads. In this section, we will simulate several scenarios in order to observe the performance of the developed TPC protocol in deferent general and network wide topologies. In the previous sections, the grid topology was adopted to confirm the methods but in WSNs, the sensor nodes are usually deployed randomly. We will examine several network topologies for various sets of the network density in order to find the optimum topology that can be recommended for further work.

To further validate the proposed hypothesis, two network topologies are suggested for a variety of network densities for a CBR application. The number of nodes simulated is 20, 40, 60, 80 and 100 nodes that were deployed at a specific area of (200×200) m^2. The radio channel frequency is 2.4 GHz for IEEE 802.11g. Table 5.4 shows the general parameters of the simulation scenarios for various network densities.

Table 5.4 Parameters of network density scenarios.

Parameter	Configuration/ type/ settings
Simulation Tool	QualNet 5.1 developed by C++
Simulation Time	100s
Simulation area	(200×200) m
Type of Node	Sensor
Number of Nodes	20, 40, 60, 80 and 100
Number of Hops	Dynamically
Routing Protocol	Multi-Path routing
Number of Path(s)	Two
Applications	CBR
Physical Layer Model PHY	802.11g
MAC Protocol IEEE	802.11

Figure 5.7 shows the two scenarios that were run based on the network topology (i.e. grid nodes' deployment and randomly nodes' deployment) to find the optimum network performance through utilising the developed multipath TPC.

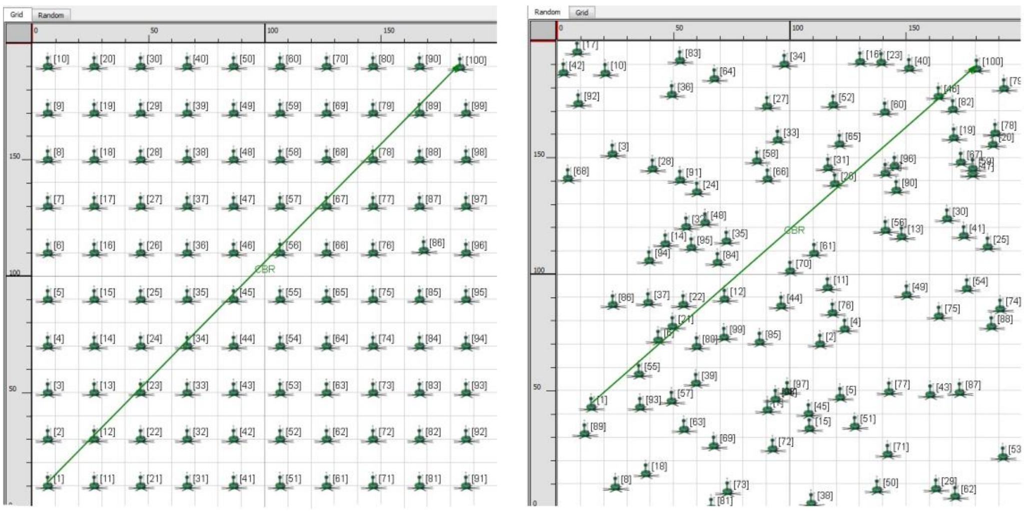

Figure 5.7 Nodes' deployment [grid (left), and random (right)].

Without doubt, energy efficiency is the most significant criteria that should be considered in the WSN design. The sensor nodes consumed the majority of their energy through the wireless communication activities. This fact dictates that all communication activities should be controlled to minimise the energy drain in WSNs. Hence, we have investigated the energy consumption based on the mathematical model for ideal assumption when the nodes are deployed as a grid (as mentioned previously). However, a TPC is developed for dense WSNs, where N

nodes are randomly deployed in a specific region in terms of network density (i.e. uniformly and non-uniformly deployment). We will evaluate the energy consumption of the developed TPC in several scenarios based on network density due to the simulation limitation of sparse WSNs (we only examined a small number of nodes to investigate the hypothesis of the combination of multi-hopping with multi-path topology). Note that, every sensor node is equipped with single-channel/single-transceiver IEEE 802.11g radio channel, and the location of the located nodes is obtained by GPS device. The simulation parameters are set as listed above in Table 5.4. Figure 5.8 shows the energy consumption average per node for deferent number of nodes. Additionally, Figure 5.9 shows the total energy consumption over the network for deferent number of nodes.

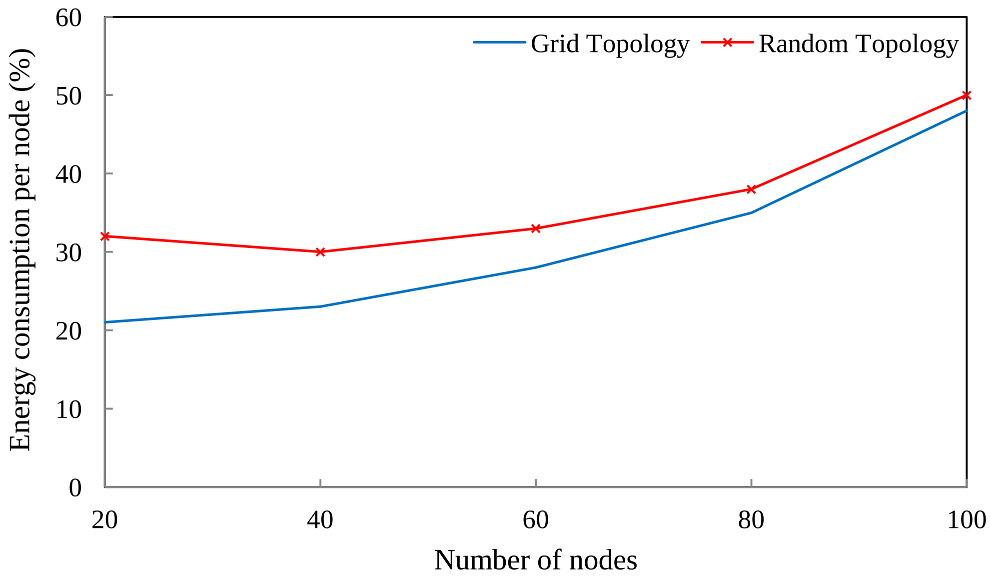

Figure 5.8 Average of the energy consumption per node.

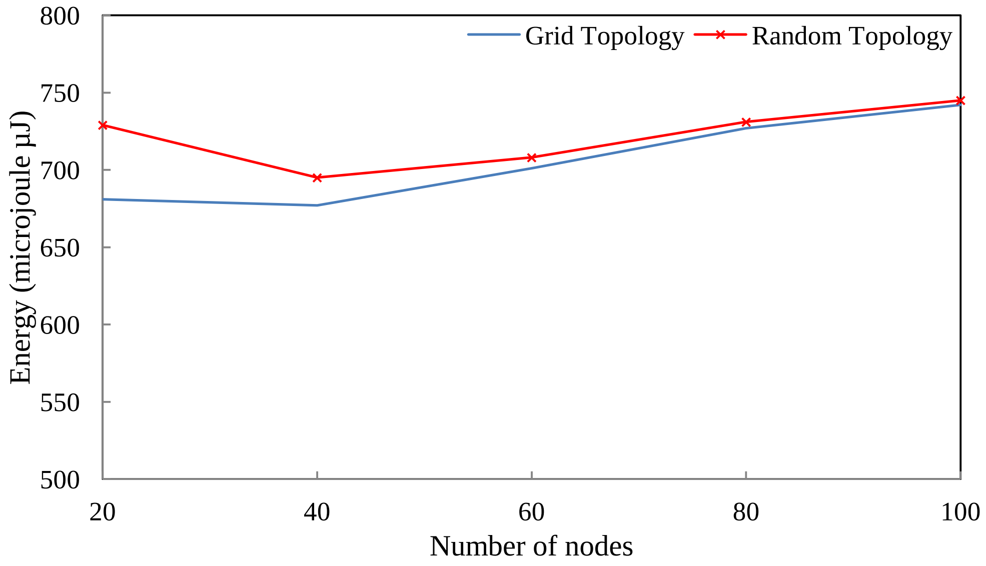

Figure 5.9 Total energy consumption.

Figure 5.8 and Figure 5.8 show that as we increase the network density, the average energy usage increases. The figures also show that more energy is consumed when the sensor nodes are randomly located at the network instead of grid topology due to the equality of the nodes' distance which can give high-stability based on unique transmission range. The results are consistent with the earlier simple topologies. As we increase the network density, effectively there are more hops on average between source and destination pairs and hence the energy usage increases. Having 40 nodes in the area results in most connections having 2 to 3 hops and hence results in the lowest amount of energy consumed and hence longest network lifetime.

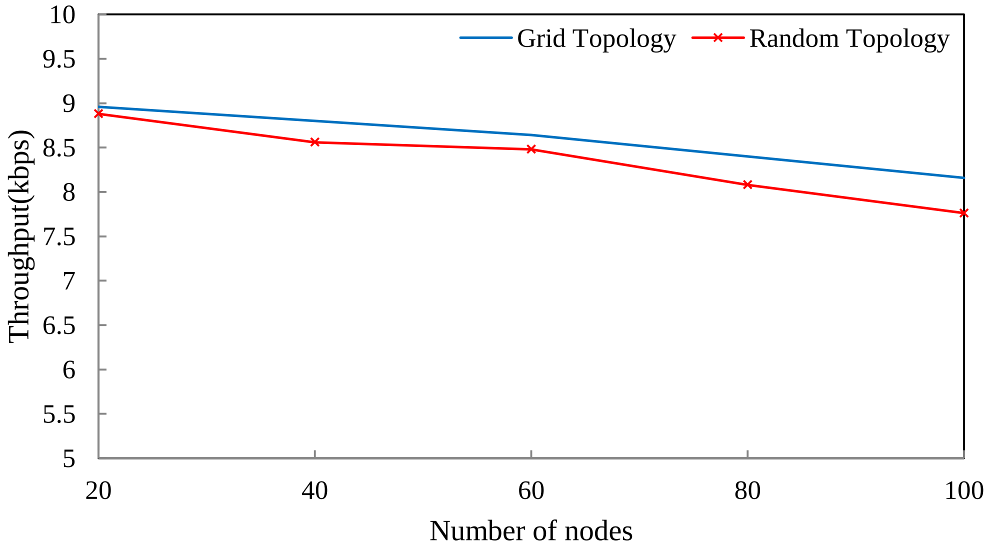

Figure 5.10 Data throughput for deferent network topologies and densities.

Figure 5.10 shows the throughout experienced by the two networks as we vary the number of nodes. The results are also expected with the throughout reducing as the number of nodes increases. This is due to many factors. First and foremost, it is due to the increasing number of hops, and secondly it is due to the increased interference as the number of nodes increases. The figure also shows that high throughput is obtained when traversing a grid network and that is to be expected.

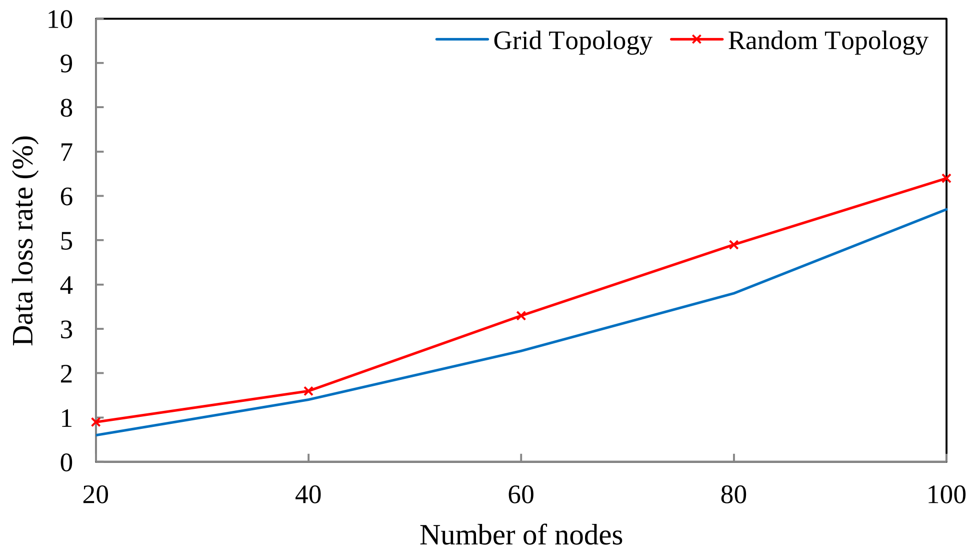

Figure 5.11 Data loss rate for deferent network topologies and densities.

Figure 5.11 also shows the corresponding data loss experienced by the nodes as the number of nodes increases.

5.5 Conclusions

By utilising QualNet 5.1 as the major simulation software, several simulation scenarios have been carried out to examine and investigate the performance of dense WSNs by taking into account the possibility of enhancing power saving and maintaining throughput at the same time. The simulation results showed that using 2, 3, 4 and 5 hops scenarios can give higher power savings than single, 6, 7, and 8 hops topologies in both cases of single and multiple paths topologies. However, utilising two, three, four and five hops in multi-path routing protocol offers noticeable enhanced energy efficiency in dense WSNs over single-hop/single-path routing protocol. The simulation results showed some energy use is improved if 2 or 3 hops are used and throughput does in fact start approaching 1 over a long enough period of time if 2 paths are used. However, the results are not close to the ideal situation that has been considered in Chapter 3. Due to the message exchange of the MAC and routing protocols and other interference in the wireless network, much throughput and power is used that any improvements become marginal.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

In this work, we looked at a research question related to high density sensor networks and more specifically, we looked at the energy and throughput characteristics of sensor networks. In this chapter, we conclude the work done and suggest some future work.

6.1 Conclusions of the current study and major outcomes

This work has attempted to answer the following research question, can the lifetime of a high density Wireless Sensor Network (WSN) be extended while maintaining throughput across it. To answer this question, we conducted an extensive literature review of current work into Transmit Power Control (TPC) and Multi-path routing. Our findings were summarised into two extensive tables in Chapter 2. It was clear that much work has been done to reduce the energy usage of sensor networks at the MAC level and the routing level. It was also clear that few works attempted to optimise both aspects of energy and throughput which became the focus of this work.

We then made the hypothesis that it maybe possible to achieve this result if we can take advantage of the inverse square law of propagation in combination with multi-path routing. In Chapter 3, it was shown for some ideal topologies that this indeed was the case. The limiting factor of throughput improvement is the single receiver of a sensor node. Hence, throughput cannot be improved if more than 2 paths were chosen.

To practically test the question, we combined the TPC features into MP-OLSR. This new protocol aims to only have two paths between source and destination and break up each path into 2 to 3 hops and a maximum of 5 hops. This was discussed in

Chapter 4. Hence, in this way power saving can be achieved while maintaining throughput.

In Chapter 5, we implemented the protocol in QualNet. The results were encouraging and showed that indeed some savings can be achieved, but they also showed that the significance of the savings is severely diminished through the IEEE 802.11 MAC protocol as well as the overheads associated with the routing protocol. The main conclusion that can be drawn is that some energy gains can be achieved but they are marginal and not significant.

Now we give a more detailed look at the conclusions:

In Chapter 3, the theoretical results showed that using multi-hop communication to save energy and control the transmission power leads to a reduction in the throughput depending on the number of hops. Therefore, a multi-path topology was proposed to keep neutral throughput. The combination of two topologies (i.e. multi-hop and multi-path) in one algorithm was proposed as a suitable solution to mitigate the disadvantages of utilising each topology individually.

In Chapter 4, the proposed algorithm involved both efficient TPC to find the optimal transmission power, and the multi-path routing protocol to maintain throughput across at least two independent paths. Base on the mathematical model, the following criteria has been adopted:

- The optimal number of hops is three at each path. Moreover, the number of hops must be between 2 and 8 ($2 \leq h \leq 8$) such that the energy consumption could be reduced if this results are considered when designing the TPC protocol;

- Neutral throughput can be achieved when utilising more than two paths; however, the optimal number of paths is two to maintain throughput when the number of packets (*N*) increases to infinity, this was due to the fact of having only one receiver, hence regardless of how many paths are present, the packets will have to wait and be received one by one at the destination node.

A TPC was combined with the MP-OLSR protocol with modifications that resulted in the new protocol.

In chapter 5, the QualNet simulation results showed some energy consumption is reduced if 2 or 3 hops are utilised and throughput is higher a long enough period of time when using two paths but it does not converge to the maximum very quickly as the theoretical model shows.

6.2 Recommendations

Although, this thesis has tried to highlight real research problems and investigate possible key solutions that face designing energy-efficient WSNs, it fails to cover other important challenges due to the time constraints. Future research work in this direction can be derived from the current study as follows.

- The developed TPC protocol can be further enhanced by considering other WSN features such as interference.

- It is of importance to investigate the impact of multi-hop communication on multi-channel/multi-transceiver WSNs to maintain throughput in a single-path topology instead of utilising multi-path routing protocols for single-channel/single-transceiver WSNs.

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