Real-time Link Quality Estimation and Holistic Transmission Power Control for Wireless Sensor Networks

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I Copyright Statement

II Abstract

Wireless sensor networks (WSNs) are becoming widely adopted across multiple industries to implement sensor and non-critical control applications. These networks of smart sensors and actuators require energy efficient and reliable operation to meet application requirements. Regulatory body restrictions, hardware resource constraints and an increasingly crowded network space makes realising these requirements a significant challenge.

Transmission power control (TPC) protocols are poised for wide spread adoption in WSNs to address energy constraints and prolong the lifetime of the networked devices. The complex and dynamic nature of the transmission medium; the processing and memory hardware resource constraints and the low channel throughput makes identifying the optimum transmission power a significant challenge. TPC protocols for WSNs are not well developed and previously published works suffer from a number of common deficiencies such as; having poor tuning agility, not being practical to implement on the resource constrained hardware and not accounting for the energy consumed by packet retransmissions. This has resulted in several WSN standards featuring support for TPC but no formal definition being given for its implementation. Addressing the deficiencies associated with current works is required to increase the adoption of TPC protocols in WSNs.

In this thesis a novel holistic TPC protocol with the primary objective of increasing the energy efficiency of communication activities in WSNs is proposed, implemented and evaluated. Firstly, the opportunities for TPC protocols in WSN applications were evaluated through developing a mathematical model that compares transmission power against communication reliability and energy consumption. Applying this model to state-of-the-art (SoA) radio hardware and parameter values from current WSN standards, the maximum energy savings were quantified at up to 80% for links that belong to the connected region and up to 66% for links that belong to the transitional and disconnected regions. Applying the results from this study, previous assumptions that protocols and mechanisms, such as TPC, not being able to achieve significant energy savings at short communications distances are contested. This study showed that the greatest energy savings are achieved at short communication distances and under ideal channel conditions.

An empirical characterisation of wireless link quality in typical WSN environments was conducted to identify and quantify the spatial and temporal factors which affect radio and link dynamics. The study found that wireless link quality exhibits complex, unique and dynamic tendencies which cannot be captured by simplistic theoretical models. Link quality must therefore be estimated online, in real-time, using resources internal to the network.

An empirical characterisation of raw link quality metrics for evaluating channel quality, packet delivery and channel stability properties of a communication link was conducted. Using the recommendations from this study, a novel holistic TPC protocol (HTPC) which operates on a per-packet basis and features a dynamic algorithm is proposed. The optimal TP is estimated through combining channel quality and

packet delivery properties to provide a real-time estimation of the minimum channel gain, and using the channel stability properties to implement an adaptive fade margin.

Practical evaluations show that HTPC is adaptive to link quality changes and outperforms current TPC protocols by achieving higher energy efficiency without detrimentally affecting the communication reliability. When subjected to several common temporal variations, links implemented with HTPC consumed 38% less than the current practise of using a fixed maximum TP and between 18-39% less than current SoA TPC protocols. Through offline computations, HTPC was found to closely match the performance of the optimal link performance, with links implemented with HTPC only consuming 7.8% more energy than when the optimal TP is considered.

On top of this, real-world implementations of HTPC show that it is practical to implement on the resource constrained hardware as a result of implementing simplistic metric evaluation techniques and requiring minimal numbers of samples. Comparing the performance and characteristics of HTPC against previous works, HTPC addresses the common deficiencies associated with current solutions and therefore presents an incremental improvement on SoA TPC protocols.

Key words: Transmission Power Control, Wireless Sensor Network, Link Quality Estimation, Channel Quality, Packet Delivery, Channel Stability, Spatio-temporal Factors.

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IV Dedication

This thesis is dedicated to my late grandfather, Bryan Elliston. Although I lost you long before you could have a direct impact on my career, the memories I have of you provide a constant reminder of the person I would like to become. I mean this not just in an engineering sense, but also in the wider context of being a well-respected, thoughtful and loving individual. I look forward to the day we meet again.

V Abbreviations

ASK – Amplitude Shift Keying

BER – Bit Error Rate

CCA – Clear Channel Assessment

CR – Communication Reliability

CSI – Channel State Information

CSMA/CA- Carrier Sense Multiple Access with Collision Avoidance

dB – Decibel

ETSI – European Telecommunications Standard International

FM – Fade Margin

FSK – Frequency Shift Keying

GFSK – Gaussian Frequency Shift Keying

HF – High Frequency

ISI – Inter Symbol Interference

ISM – Industrial, Scientific and Medical

LOS – Line-of-sight

LQE – Link Quality Estimator

LQI – Link Quality Indicator

LQT – Link Quality Threshold

MAC – Medium Access Control

MSK – Minimum Shift Keying

NLOS – Non-line-of-sight

PER – Packet Error Rate

PHY- Physical

PRR – Packet Reception Rate

RNP – Required Number of Packet Transmissions

RSSI – Receive Signal Strength Indicator

SINR – Signal-to-interference-and-noise ratio

SNR – Signal-to-noise ratio

SoA – State-of-the-art

TI – Texas Instrument

TP – Transmission Power

TPC – Transmission Power Control

WMEWMA – Window Mean with Exponentially Weighted Moving Average

WSN – Wireless Sensor Network

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Chapter One: Introduction

1.0 Background

With the integration of sensing, processing and communication abilities in small form factor devices, wireless sensor networks (WSNs) are becoming widely adopted across multiple industries to implement sensor and non-critical control applications. These networks of smart sensors and actuators require energy efficient and reliable operation to meet application requirements. Regulatory body restrictions, hardware resource constraints and an increasingly crowded network spaces makes realising these requirements a significant challenge.

One of the most severe resource constraints in WSNs is energy [1]. Energy constraints are the result of cost and form factor requirements limiting the type, size and capacity of the battery store. The available energy is typically finite and cannot be replenished during the lifetime of the device due to the inability or infeasibility of battery charging and replacement. Future WSNs are expected to have orders of magnitude lower energy capacity [2] as a result of replacing traditional energy supplies for super capacitor, paper-thin battery and energy harvesting solutions. Subsequently, there is a growing need to optimise common activities through energy efficient algorithms and protocols to address energy constraints and prolong the lifetime of the networked devices.

Previous works have found that wireless communication activities are often the most energy consuming that a WSN node performs [3] and as such, optimising this activity is seen as pivotal to achieve battery life requirements. A large number of works have been devoted to increasing the energy efficiency of wireless communication activities in WSNs and have proposed optimising several radio parameters, including; data rate [4], packet routing [5] and duty cycle [6]. Alongside these, several works have proposed schemes that modulate the transmission power (TP). This practise is commonly referred to as transmission power control (TPC). Through the implementation of a TPC protocol, nodes dissipate the minimum amount of energy required to ensure error free reception at the receiver. This reduces the number of packet retransmissions and the number of packets transmitted with excessive energy for the intended recipient.

The implementation of a TPC protocol faces several challenges. The most prominent of these is characterising the communication link in order to identify the optimum TP. Communication links have been shown in several empirical studies ([7] [8] [9] [10]) to be affected by spatio-temporal factors which result in them experiencing complex and dynamic tendencies. The effect of these factors is more severe in WSNs since low-power radios are used and the link budget is limited. Consequently, radio links in WSNs are often unpredictable and their quality fluctuates over time ([11] [12]) and space ([7] [9]). On top of this, WSNs are constrained in memory and computational complexity domains, and channel throughput is typically very low. Therefore, only protocols and mechanisms which feature low processing, memory and sampling overheads are practical to implement [1].

1.1 Motivation

TPC protocols with the primary objective of increasing the energy efficiency of wireless communication activities have been shown in several works to be highly effective, with up to 80% energy savings deemed possible in [13]. On top of this, TPC protocols designed for energy efficiency objectives have the potential to make improvements to the following aspects of communications in WSNs:

1. **Spectrum efficiency.** When nodes communicate at the minimum TP needed to ensure a successful reception, the communication and interference radii are nothing broader than needs be. Thus, only nodes which really must share the same space will contend to access the medium. The interference suppression offered by a TPC protocol subsequently enhances the network utilisation, lowers latency times and helps to ensure co-existence with other wireless networks.
2. **Packet delivery.** When nodes transmit at a given TP that results in sufficient signal-to-noise ratio (SNR) at the receiver, the bit error rate can be constrained. Links with poor communication reliability as a result of inadequate SNR can be improved through leveraging the features of a TPC protocol and using a more suitable TP.

There has been extensive research on TPC protocols in wireless networks, studied in several contexts and optimised for different objectives. However, the use of TPC in short-range, low-power WSNs is relatively new and as such, the algorithms are not well developed. Despite some promising results, current TPC protocols suffer from numerous deficiencies which limits their performance. These include:

1. **Not practical to implement on WSN hardware.** Many current TPC protocols have proposed link quality estimation techniques which are computationally expensive and/ or require a large number of samples to be cached. Due to the typical resource constraints of WSN hardware (namely limited memory and processing resources), existing solutions are often impractical to implement.
2. **Poor accuracy.** Several works on TPC have experienced poor energy efficiency and/ or reliability, particularly when the link quality has dynamic tendencies. This is primarily due to deficiencies in the link quality estimation process which result in the TP not being optimised to the actual channel conditions.
3. **Poor tuning agility.** Current TPC protocols leverage metric evaluation techniques and tuning algorithms which are slow to react to changing channel conditions. This results in the TP being poorly optimised to current channel conditions and detrimental effects to energy efficiency and/ or communication reliability. This is exacerbated by the dynamic link conditions experienced in WSN applications.
4. **Optimised for different objectives.** Several TPC protocols have been proposed with the primary objective of enhancing throughput, increasing connectivity and reducing delays. Since energy is the fundamental resources constraint in WSNs, TPC protocols with the primary objective of increasing the energy efficiency are of most relevance.

5. **Optimised for a single application.** Many current TPC protocols are modelled, optimised and tested on single applications with specific environmental factors and wireless properties. Since WSNs cover a plethora of application areas, the performance of the TPC protocol needs to be optimised over various link conditions and radio configurations.

6. **Based on theoretical study and simulations.** Although theoretical study and simulations provide a valuable and solid foundation, solutions found by such efforts are often ineffective in real running systems. This is because they are based on simplified assumptions which are not representative of actual channel conditions, such as; static link quality, perfect modulation accuracy and continuous TP levels.

7. **Do not account for the energy consumed by packet retransmissions.** Almost all link layer protocols used in WSNs use packet acknowledgement and retransmission mechanisms to improve the communication reliability. Many current works on TPC have failed to account for the energy consumed by packet retransmissions so the reported energy savings are often unrepresentative of the actual performance of the protocol.

Several WSN standards (such as Bluetooth Low Energy [14], WirelessHART [15] and ISA100.11a [16]) feature support for TPC but no formal definition is given for its implementation [17]. The author believes this is a result of the aforementioned deficiencies which limit the performance of state-of-the-art (SoA) TPC protocols. Addressing these deficiencies is therefore necessary to increase the adoption of TPC protocols in WSN applications.

1.2 Aims and Objectives

The aim of this research is to design, implement and test an application independent TPC protocol with the primary objective of increasing the energy efficiency of wireless communication activities in WSNs. The protocol should leverage simplistic metric evaluation techniques and require a small number of samples to be cached so that it is practical to implement on the resource constrained hardware and the sampling requirements can be achieved in typical WSN applications.

The approach used in this research follows a series of ordered objectives, as detailed below:

1. Review of TPC practices and current solutions.

2. Review of the literature on wireless channel models and measurements.

3. Develop mathematical models that compare TP against communication reliability and energy consumption to quantify the potential energy savings of a TPC protocol.

4. Evaluate the link conditions typically experienced in WSN applications.

5. Evaluate the performance of link quality metrics for the purpose of capturing the properties of the communication link required to identify the optimum TP.

6. Design and optimisation of a new TPC protocol.

7. Evaluation of the new TPC protocol.

1.3 Publications and Novelty

The principal contributions of this works are as follows:

- The opportunities for TPC protocols in WSN applications have been evaluated through developing a mathematical model that compares TP against communication reliability and energy consumption. Applying this model to SoA radio hardware, the maximum potential energy savings were quantified and the link conditions which offered the greatest opportunities were identified.
- An empirical characterisation of wireless link quality in typical WSN environments was conducted. Through this, the spatial and temporal factors which affect radio and link dynamics in WSNs were identified and quantified.
- An empirical characterisation of raw link quality metrics for evaluating channel quality, packet delivery and channel stability properties of the communication link is presented. From this, recommendations on the most suitable metrics to use for a TPC protocol are made. The evaluation can also be used to assess the link quality metrics used in future works on TPC and utilised in the design of other link quality estimators with minor amendments.
- A novel holistic TPC (HTPC) protocol with the primary objective of increasing the energy efficiency of communication activities in WSN applications is proposed. HTPC captures channel quality, packet delivery and channel stability properties of the communication link using low computational complexity and memory techniques. Practical evaluations show that HTPC is practical to implement on the resource constrained hardware, adaptive to link quality changes and outperforms current SoA TPC protocols.

Part of this work has been published and presented in the following international conferences and journals.

- J. Hughes, G. Horler, E. Morris, "Transmission power control for wireless sensor networks in railway environments," in *Proc. 3rd Int. Conf. on Railway Technology: Research, Development and Maintenance*, Cagliari, Italy, 2016.
- E. Morris, G. Horler, J. Hughes "An architecture for efficient distribution of railway asset performance metrics," in *Proc. 3rd Int. Conf. on Railway Technology: Research, Development and Maintenance*, Cagliari, Italy, 2016.
- J. Hughes, G. Horler, E. Morris, "An investigatory study into transmission power control for wireless sensor networks in railway applications," in *Proc. 7th IET Conf. on Railway Condition Monitoring*, Birmingham, UK, 2016.

- G. Horler, E. Morris, J. Hughes, "Asset clamp force measurement and remote condition monitoring using a smart washer: a case study of railway research, innovation and technical delivery in the early 21st century," in *IMechE Proc. Stephenson Conference: Research for Railways*, London, UK, 2017.
- J. Hughes, P. Lazaridis, I. Glover, A. Ball, "Opportunities for transmission power control protocols in wireless sensor networks," in *IEEE Proc. Int. Conf. Automation and Computing*, Huddersfield, UK, 2017.
- J. Hughes, P. Lazaridis, I. Glover, A. Ball, "A survey of link quality properties related to transmission power control protocols in wireless sensor networks,", in *IEEE Proc. Int. Conf. Automation and Computing*, Huddersfield, UK, 2017.
- J. Hughes, P. Lazaridis, I. Glover, A. Ball, "An empirical study of link quality assessment in wireless sensor networks applicable to transmission power control protocols," in *IET Loughborough Antennas and Propagation Conf.*, Loughborough, UK, 2017.
- J. Hughes, P. Lazaridis, I. Glover, A. Ball, "A novel transmission power control protocol for wireless sensor networks," in *PGR Conf. Huddersfield*, UK, 2017.
- J. Hughes, P. Lazaridis, I. Glover, A. Ball, "Real-time link quality estimation and holistic transmission power control for wireless sensor networks," *IET Wireless Sensor Sys.*, 2018, to be published.

1.5 Thesis Structure

The rest of the thesis is organised as follows:

- Chapter 2 reviews the relevant literature related to TPC protocols for WSN applications. This includes an overview of WSN technology, TPC techniques, wireless channel modelling and link quality estimation.
- Chapter 3 presents mathematic models to quantify the opportunities for TPC protocols in WSN applications.
- Chapter 4 provides an empirical characterisation of wireless link quality in typical WSN environments.
- Chapter 5 provides an assessment of link quality metrics for evaluating the channel quality, packet delivery and channel stability properties of the communication link.
- Chapter 6 presents the design of a new TPC protocol.
- Chapter 7 provides an evaluation of the proposed TPC protocol.
- Chapter 8 draws together the conclusions and makes suggestions for future work.

Chapter Two: Literature Review

The following sub-sections review the relevant literature, which has been classified into four categories:

1. **Introduction to wireless sensor networks (WSNs).** A review of WSN technology, highlighting the characteristics, constraints and opportunities.
2. **Transmission power control (TPC) techniques.** An overview of TPC techniques and analysis of current solutions.
3. **Wireless channel modelling.** A review of the principles of wireless communications and presentation of suitable models and algorithms to describe the relationship between transmission power (TP) and link quality.
4. **Link quality estimation and distribution.** An overview of the link quality estimation process and a high-level review of current solutions.

2.0 Introduction to Wireless Sensor Networks

WSNs can be regarded as distributed sensor systems that facilitate a range of monitoring and non-critical control applications. They consist of a large set of autonomous wireless sensing nodes that are deployed over a sensing field. Each node is a low-power device capable of sensing physical information from the surrounding environment (e.g. temperature, load, vibration). As well as application specific sensors, each node features a battery, microcontroller and radio. These hardware components are used to perform sensing, processing and communication tasks. The data generated at the nodes is forwarded, possibly via multiple hops, through wireless links to a local collection point (commonly referred to as a sink). The sink can use the data locally or upload it to another network (e.g. the internet) through a gateway.

WSN nodes may be stationary or moving, and can cover many short-range network spaces, from body-area to neighbourhood-area networks. WSNs have specific traffic patterns and network topologies which are strongly application dependent and exhibit key properties from ad-hoc networks, including; decentralised control, common transmission channel, broadcast nature and ephemeral topologies [18]. A plethora of wireless standards and proprietary solutions are currently used to target the unique characteristics and challenges presented by WSNs.

WSNs are severely constrained in energy, processing and memory domains. As described in *1.0 Background*, energy constraints are the result of cost and form factor requirements limiting the type, size and capacity of the battery store. Processing and memory constraints are the result of using low-cost and low-power microcontrollers to run the host protocol stack and interface with peripherals. In order to develop systems that run unattended without battery replacement for arbitrarily long time periods (e.g. years), lightweight protocols and algorithms (in terms of computational complexity and memory usage) are required to increase the energy efficiency.

2.1 Transmission Power Control Techniques

2.1.1 Introduction

TPC is the intelligent selection of transmission output power in a wireless communication system and can be used to improve several performance properties, including; range, energy efficiency, network capacity and reliability. In the context of this thesis, the primary focus is on TPC applicable to energy efficiency objectives. However, through the implementation of a TPC protocol with energy efficiency objectives, improvements to network utilisation and communication reliability are probable (as described in *1.1 Motivation*).

The generic control loop which forms the basis of a TPC protocol is presented in Figure 1. The control loop shows transmitter operating at a TP of P_t and a receiver having an input power of P_r. The block labelled 'radio channel' represents the signal attenuation as it propagates through the medium. The signal power (P_s) is subjected to interference (P_i) and noise (P_n) at the receiver. Feedback of the received signal is then sent back to the transmitter so the TP used in subsequent transmissions can be optimised.

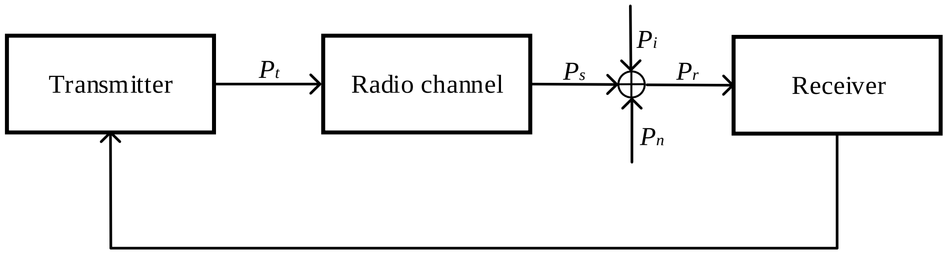


Figure 1. *Generic TPC protocol control loop.*

The ability to control the TP is available on most radio platforms. As an example, the Texas Instrument (TI) CC2420 radio present in the Crossbow MicaZ motes, provides 8 TP levels (ranging from -25 to 0 dBm), selectable at runtime by configuring a register [19]. The output power and power consumption in transmit mode when different TP levels are considered are shown in Table 1. Clearly, the higher the TP, the higher the power consumption. The range, amount and granularity of TP levels are hardware dependent.

TP level	Output power (dBm)	Output Power (mW)	Power consumption (mW)
1	-25	0.003	25.5
2	-15	0.032	29.7
3	-10	0.100	33.6
4	-7	0.200	37.5
5	-5	0.316	41.7
6	-3	0.501	45.6
7	-1	0.794	49.5
8	0	1.000	52.2

Table 1. *Power consumption of the TI CC2420 radio in TX mode at different TP levels [19].*

The basic operating principle of a TPC protocol is to configure the TP to a level that results in the minimum energy dissipated per transaction[1] (E_{trans}), whilst still allowing a predefined level of reliability to be achieved. This principle is demonstrated in Figure 2.

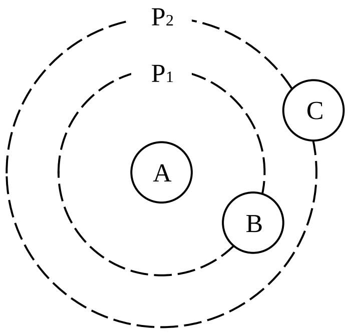


Figure 2. *High-level overview of TP against communication range.*

The diagram in Figure 2 illustrates a network consisting of one transmitting node (A) and two receiving nodes (B and C). In order for packets transmitted from node A to be successfully received by nodes B and C, the minimum TP levels are P_1 and P_2, respectively. If the transmitting node uses a fixed TP of P_2 for all packet transmissions, packets received at node B will have excessive energy. This results in poor energy efficiency at the transmitting node because packets could have been sent at a lower TP and still be successfully received. Conversely, if a TP of P_1 is used for all packet transmissions, the communication radius would be too small for node C. This would result in poor communication reliability and energy efficiency because of insufficient link budget causing packet retransmissions. To maximise the energy savings and ensure that detrimental effects to communication reliability aren't realised, the TP needs to be configured on a per-link basis.

2.1.2 Transmission Power Control Modelling

TPC protocols are based upon models that describe the relationship between TP, E_{trans} and communication reliability (CR). CR is often measured by the packet reception ratio (PRR) or similar packet delivery properties. The relationship between TP, E_{trans} and CR was characterised empirically in [13] and found to exhibit the characteristics shown in Figure 3. This relationship is further analysed in *3.3 Generalised Energy Model*.

[1] A transaction is a data exchange event between a transmitter and receiver, and may consist of multiple packet retransmissions if a successful packet transmission is not detected (i.e. not acknowledged).

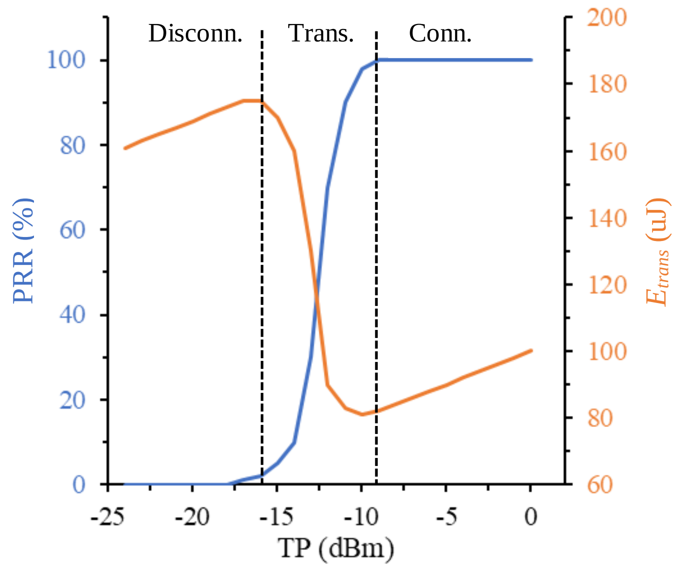


Figure 3. *Relationship between TP, E_{trans} and PRR.*

The graph in Figure 3 can be seen to have three distinct regions which determine the relationship between TP, E_{trans} and CR. These are:

- **Connected region (Conn)**. In the connected region, reducing the TP minimises the E_{trans}. The CR is not affected by the TP (i.e. PRR > 95%) because of sufficient link budget.
- **Disconnected region (Disconn)**. In the disconnected region, reducing the TP also reduces the E_{trans}. However, E_{trans} is significantly higher than in the connected region because each transaction consists of multiple packet retransmissions. In the disconnected region, there is insufficient link budget for successful packet delivery so the CR remains poor (i.e. PRR < 5%), irrespective of the TP level used.
- **Transitional region (Trans)**. The relationship between TP and E_{trans} / CR is sigmoidal in the transitional region, with a small change in TP significantly affecting the other two properties.

From Figure 3, it can be seen that the TP that results in minimal E_{trans} exists on the boundary between the transitional and connected regions. As a result of the steep increase in E_{trans} and the negative effect on CR, it is preferable to use a slightly higher TP so that the link exists in the connected region rather than the transitional region.

Previous empirical studies into the correlation between TP and link quality ([10] [20] [21]) have highlighted that the optimum TP is application dependent and will vary over time due to the spatio-temporal factors of the transmission medium. For this reason, the wireless link quality needs to be continually evaluated so that the optimum TP can be identified, applied and maintained during operation.

2.1.3 Transmission Power Control Design Considerations

Since TPC protocols operate in a distributed manner, certain undesirable side effects are inevitable. These are predominately the resultant of communication and carrier sense radii being suppressed as a result of reducing the TP. The design of an efficient TPC protocol has to take these effects into account. A previous study into TPC protocols for IEEE 802.11 networks ([22]) has highlighted that TPC can exacerbate hidden and exposed nodes issues, as well as introduce channel asymmetry between links operating on the same channel. The interaction between two networks with TPC applied are summarised in Figure 4 and described below.

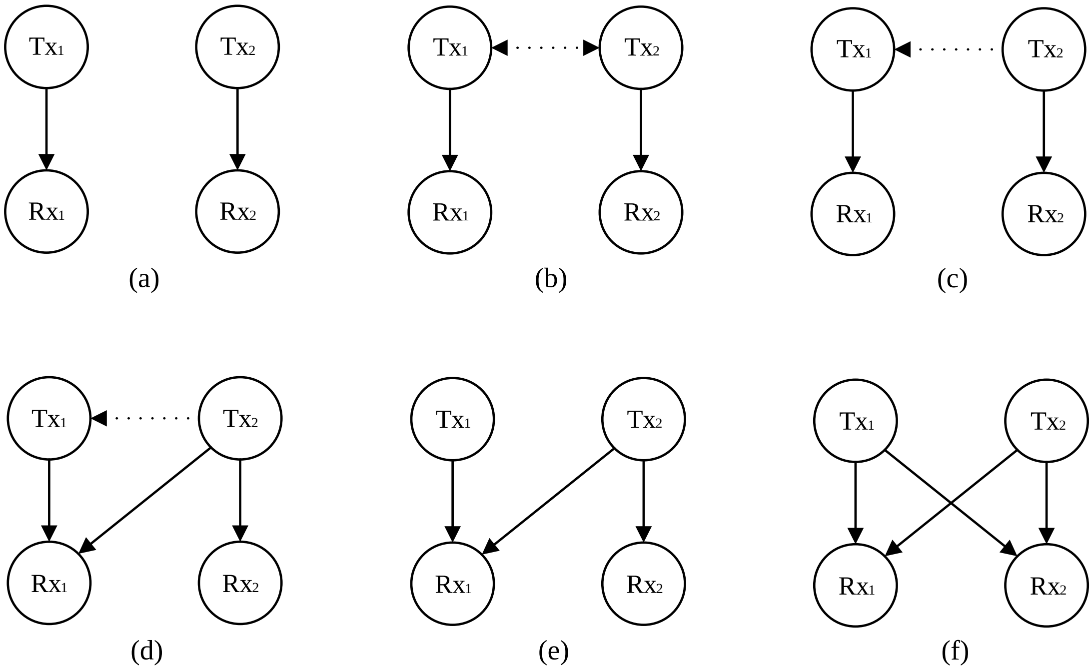


Figure 4*. Interaction between two networks with TPC applied [22].*

Transmitters and receivers are represented by Tx and Rx blocks, respectively. A solid arrow (→) from Tx to Rx indicates that the Rx is in the communication range of Tx. A dashed arrow (- - >) from Tx_1 to Tx_2 indicates that Tx_2 can carrier sense Tx_1 (i.e. Tx_2 can hear Tx_1's transmissions so will not transmit at the same time).

The six scenarios are:

- Scenarios *a* and *b* in Figure 4 represent best-base scenarios, where the two networks do not detrimentally affect one another when TPC has been applied. This is a result of both networks either having separate network spaces (scenario *a*) or both networks being able to successfully share the same network space (scenario *b*).
- Scenario *c* represents the exposed node problem that results in channel access asymmetry. The link between Tx_1 and Rx_1 is starved since Tx_2 cannot hear Tx_1's transmissions so always perceives a clear channel. Due to the low throughput characteristics of WSNs, the latency introduced by this scenario will be minimal and thus, will not pose significant issues.

- Scenario *d* also represents the exposed node problem but this time it manifests itself in the form of packet losses at Rx_1 due to simultaneous transmissions by Tx_1 and Tx_2 causing packet collisions at Rx_1.
- Scenarios *e* and *f* represent the hidden node problem. The transmitters (Tx_1 and Tx_2) are not in each other's carrier sense range and hence the problem again manifests itself as packet losses at Rx_1 and/or Rx_2 due to simultaneous transmissions.

To the best of the author's knowledge there are no previous studies on the occurrence of the six scenarios presented in Figure 4 for WSN deployments. These have however been studied for unplanned dense deployments of IEEE 802.11 networks in [22] and [23], and were found to be highly probable because of their high throughput characteristics. Detecting and avoiding these problems in mobile environments was also found to be challenging since they can be dynamically introduced for short time periods. Although the probability of these scenarios occurring in WSNs is lower due to the low throughput characteristics of WSN applications and regulatory body restrictions, they are still predicted to degrade the performance of the network and therefore must be addressed.

In [24] the medium access control (MAC) protocol specified by the IEEE 802.15.4 standard, which is commonly used in WSNs, was studied with TPC enabled. This study observed that the nodes experienced lower communication reliability when TPC was enabled. The link unreliability was believed to be linked with limitations of the carrier sense multiple access with collision avoidance (CSMA/CA) algorithm, which resulted in scenarios *d*, *e* and *f* occurring. Although it was shown in [24] that in some cases with appropriate parameter settings the communication reliability can be improved, these parameters were often not compliant with the standard.

In [22] it was recommended that the packet delivery properties of the link are monitored to address the exposed and hidden node issues. Through monitoring packet delivery properties of the communication link, the TP could be increased to either leverage the capture effect or to bring the interfering transmitter within the carrier sense range. Both techniques would have a desirable effect and would allow for scenarios *d*, *e* and *f* to be identified and mitigated. Many previous works on TPC presented in the literature (further details provided in *2.1.6 Related Works*) do not account for packet delivery properties so are unable to identify and mitigate against the exposed and hidden node issues. These protocols are therefore likely to suffer from performance degradation due to packet losses.

2.1.4 Transmission Power Control Protocols

TPC protocols can be categorised into four different categories depending upon the configurability of the TP. These are:

- **Network-level.** A single fixed TP is used for all communications within the network (for example [25]).
- **Node-level**. Every node uses a single fixed TP for all its neighbours (for example [26]).
- **Neighbour-level.** Each node uses a different fixed TP for each neighbour (for example [27]).

- **Packet-level**. The TP is configured on a per-packet basis (for example [28]).

Previous research works ([9] [10] [29]) have concluded that the quality of a communication link between an arbitrary distance transmitter and receiver is unique, and is dynamic in nature. For the full benefits of a TPC protocol to be realised, a packet-level solution is required. To implement a packet-level TPC protocol, the quality of each communication link needs to be continually evaluated and information about this distributed in the network. This process can result in additional memory, computation and energy overhead so efficient design practices need to be applied.

2.1.5 Transmission Power Control Algorithms

As documented in [30], TPC protocols use one of the following algorithms:

- **Linear**. Linear TPC algorithms change the TP linearly, step-by-step, through comparing the link quality against upper and lower thresholds. The gradual change in TP offered by this technique results in the optimum TP being reached in a conservative manner.
- **Binary**. Binary TPC algorithms operate in a similar manner to linear algorithms but the step size change in TP is exponential. This type of approach is more aggressive than linear algorithms and the optimal TP is reached much sooner but there is an increased risk of detrimental effects to the communication reliability.
- **Dynamic**. Dynamic TPC algorithms directly determine the optimal TP from a predefined relationship between TP and the link quality property.

An assessment carried out in [30] observed that dynamic algorithms yielded the best performance from reliability and energy efficiency perspectives because of their low latency characteristics. However, dynamic algorithms typically consume more memory and processing resources than other approaches so care must be taken to ensure they are practical to implement on the resource constrained hardware.

2.1.6 Related Works

TPC protocols have been studied extensively in the literature; in several different contexts and with several different objectives. This has resulted in TPC protocols being produced for multiple wireless technologies, including; cellular ([31]), mobile ad-hoc ([32]), vehicular ad-hoc ([33]), and wireless local area networks ([34]). TPC strategies and methods for traditional networks cannot simply be replicated for WSNs. Reasons for this include regulations surrounding the use of industrial, scientific and medical (ISM) radio bands, the availability of link quality metrics and resource constraints of the hardware. Because of these important differences, only TPC protocols which consider WSN applications and that are optimised for energy efficiency objectives have been considered. A taxonomy of the most relevant TPC protocols for WSN applications is presented in Table 2 (page 29).

In [10], Lin et al. proposed ATPC; an adaptive TPC protocol which modulates the TP on a per-packet basis using an autoregressive filter on RSSI samples. The protocol was tested in pseudo-static environments and was found to achieve significant energy savings. Correia et al. in [35] developed ATPC to include battery voltage and noise power measurements. Xiao et al. in [2] and Lee et al. in [30] proposed similar channel quality based TPC protocols. These were optimised and tested in healthcare applications with high throughput. Although the aforementioned works present protocols with significant energy savings, they were tested in best case scenarios, i.e. static network conditions or dynamic network conditions with high throughput. On top of this, they required large numbers of samples which are often impossible to achieve because of the low throughput characteristics of WSN applications and impractical to implement on the resource constrained hardware. The TPC proposed in this thesis differs as it has been designed to be application independent and as such, its performance has been optimised and analysed over various link conditions using both simulated and practical approaches. Moreover, it is practical to implement on the resource constrained hardware because it requires few samples and leverages simplistic metric evaluation techniques.

In [29], [17] and [36], TPC protocols which capture channel quality and channel stability properties were proposed. These works all quantified the channel quality properties through measuring the power at the receiver (Receive signal strength indicator, RSSI) and the channel stability properties through quantifying the variance in the RSSI metric. The aforementioned works commonly argued that channel stability properties need to be captured to address estimation errors which are often the result of link quality changes between measurement and operational windows. The low channel throughput characteristics of WSN applications coupled with the dynamic tendencies of the transmission medium, were found to lead to large estimation errors in [29]. Observations presented in previous works highlight that channel stability properties need to be captured to ensure energy efficient and reliable operation.

In [37], B-MAC-PCI is proposed which only captures the packet delivery properties of the communication link. This study observed that some of the detrimental effects to communication reliability, which can often be exacerbated through the implementation of a TPC protocol (most noticeable increased likelihood of hidden and exposed node issues because of the interference and communication radii are supressed [22]), can be addressed through capturing packet delivery properties. Despite this, the protocol was found to only achieve minimal energy savings because it suffered from poor agility as a result of using a linear tuning algorithm. This work highlights that packet delivery properties should complement, rather than replace, channel quality properties.

The aforementioned, state-of-the-art TPC protocols have presented some promising results and therefore act as a solid foundation. However, they all suffer from one or more common deficiencies. These are summarised below and referenced in Table 2 (page 29).

1. **Not practical to implement in WSN hardware.** Many of the current TPC protocols utilise link quality estimation techniques which are computationally expensive and/ or require a large number of samples to be cached so are not practical to implement on the resource constrained hardware. For example, in AMC-TPC [17] over 4000 samples need to be cached to analyse the relationship between TP and link quality.

2. **Poor accuracy.** Several works on TPC have experienced poor energy efficiency and/ or communication reliability, particularly when the link quality has dynamic tendencies. For example, ATPC [10], BMAC-PCA [35] and Hybrid [30], do not offer interference mitigation so there will be errors in the link quality estimate when these protocols are implemented into real-world WSNs.
3. **Poor tuning agility.** Current TPC protocols have leveraged metric evaluation techniques and tuning algorithms which are slow to react to changing channel conditions. For example, B-MAC-PCA [35] and RSSI/LQI TPC for BANs [36] implement linear TPC algorithms. As described in *2.1.5 Transmission Power* Control Algorithms, linear algorithms only allow the TP to be changed by one level at a time. When linear algorithms are implemented in networks which have low throughput and/ or dynamic link conditions, the TP will be poorly optimised to the current channel conditions and detrimental effects to the communication reliability and energy efficiency are likely.
4. **Optimised for different objectives.** Several TPC protocols have been proposed with the primary objective of enhancing throughput ([38]), increasing connectivity ([39]) and reducing delays ([40]). Since energy is the fundamental resources constraint in WSNs, TPC protocols with the primary objective of increasing the energy efficiency are of most relevance.
5. **Optimised for a single application.** Many current TPC protocols are modelled, optimised and tested on single applications with specific environmental factors and wireless properties. For example, ATPC for WBANS [29], TPC in WBANs for healthcare monitoring [2], RSSI/LQI TPC for BANs [36] and Hybrid [30] have only been tested in healthcare applications with high throughput. Since WSNs cover a plethora of application areas, the performance of the TPC protocol needs to be optimised over various link conditions and radio configurations.
6. **Based on theoretical study and simulations.** Although theoretical study and simulations provide a valuable and solid foundation, solutions (such as [29]) found by such efforts are often ineffective in real running systems. This is because they are based on simplified assumptions which are not representative of actual channel conditions, such as; static link quality, perfect modulation accuracy and continuous TP levels.
7. **Do not account for the energy consumed by packet retransmissions.** Almost all link layer protocols used in WSNs use packet acknowledgement and retransmission mechanisms to improve the communication reliability. Practical evaluations of ATPC [10], B-MAC-PCA [35] and RSSI/LQI TPC for BANs [36] did not account for the energy consumed by packet retransmissions. As such, the energy savings reported by the aforementioned works are often impossible to achieve in real-world implementations.

Protocol	Hardware implementation (transceiver)	Application(s)	Performance metric(s)	Interference mitigation	Link quality properties			Hardware independent	Pre-configuration	Algorithm	Deficiencies
					Channel Quality	Packet Delivery	Channel Stability				
ATPC [10]	MicaZ (Chipcon CC2420, IEEE 802.15.4 compliant)	Not explicit	Receiver sensitivity and RSSI. Link quality indicator (LQI) shown to work.	Not explicit	X			Yes (if LQI not used)	No	Dynamic	1, 2,6
B-MAC-PCI [35]	Mica2 (Chipcon CC1000, IEEE 802.15.4 compliant)	Not explicit	Packet ACKs	Not explicit		X		Yes	Yes. Thresholds for the number of packet ACK/NAK before TP is modified are programmaticall y implemented.	Linear	2, 3
B-MAC-PCA [35]	Mica2 (Chipcon CC1000, IEEE 802.15.4 compliant)	Not explicit	RSSI, Noise, battery voltage and receiver sensitivity.	Not explicit	X			Yes	Yes. Values of receiver sensitivity and SINR threshold are programmaticall y implemented.	Dynamic	2, 6
ATPC for WBANs [29]	No practical implementation, based on results from [41].	Healthcare applications in BANs.	Receiver sensitivity, RSSI (autoregressiv e filter)	Not explicit	X		X	Yes	Yes. Values of receiver sensitivity are programmaticall y implemented.	Dynamic	5, 6
TPC in WBANs for healthcare	MicaZ (Chipcon CC2420, IEEE 802.15.4 compliant)	Healthcare applications in BANs.	RSSI (weighted average), upper and	Not explicit	X			Yes	Yes. Upper and lower thresholds for RSSI and averaging	Binary	2, 3, 5, 6

monitoring [2]			lower thresholds of RSSI.						weight of improving/ deteriorating channel are programmatically implemented.		
AMC-TPC [17]	Unknown (Texas Instrument CC2430, IEEE 802.15.4 compliant)	Industrial automation and control.	RSSI, SINR upper (based on channel stability) and lower threshold.	Yes	X		X	Yes	Yes. SINR reference is programmatically implemented.	Dynamic	1, 5
RSSI/LQI TPC for BANs in healthcare environment [36]	TMote Sky (Chipcon CC2420, IEEE 802.15.4 compliant)	Healthcare applications in BANs	RSSI, LQI, variable upper threshold of RSSI (based on channel stability)	Yes	X		X	No	Yes. Target lower threshold of RSSI and averaging weight of improving/ deteriorating channel are programmatically implemented.	Linear (one level decrease for improving link, two level increase for degrading link)	5, 6
Hybrid [30]	Mica2 (Chipcon CC1000, IEEE 802.15.4 compliant)	Healthcare applications in BANs.	RSSI, fixed upper and lower thresholds of RSSI.	Not explicit	X			Yes	Yes. Upper and lower thresholds for RSSI are programmatically implemented.	Binary (for static environments) and linear (for dynamic environments).	2, 3, 5, 6, 7

Table 2*. Taxonomy of state-of-the-art TPC protocols for WSNs.*

As seen in the above analysis, TPC protocols for low-power WSNs are not well developed. The author believes the following design challenges need to be addressed to increase the adoption of TPC protocols in WSN applications:

- Precise tuning algorithm which allows for the maximum energy savings to be achieved without detrimentally affecting the communication reliability.
- Minimal memory and computation overhead so it is practical to implement on the resource constrained hardware.
- Application, hardware and standard agnostic.
- Adaptive to link quality changes.

2.1.7 Summary

This sub-section can be summarised as follows:

- TP/ CR/ E_{trans} models show that energy savings are only available up to a certain limit and beyond this, detrimental effects to the energy efficiency and communication reliability are highly probable.
- The unique and dynamic nature of wireless communication links result in packet-level protocols and dynamic algorithms yielding the optimum performance. These approaches do however require more memory and computation resources than other approaches so efficient design is necessary to ensure the protocol is practical to implement.
- Hidden and exposed node issues can be exacerbated through the implementation of a TPC protocol. These effects can be identified and mitigated through capturing the packet delivery properties of the communication link.
- There has been extensive research on TPC protocols but their use in low-power WSNs is relatively new. As such, the solutions are not well developed and they suffer from a number of common deficiencies which limits their performance. Addressing the common deficiencies is necessary to increase the adoption of TPC protocols in WSNs.

2.2 Wireless Channel Modelling

2.2.1 Introduction

To implement a measurement based TPC protocol, the underlying characteristics of the wireless communication link need to be analysed and the relationship between TP and link quality needs to be defined. This subsection aims to:

- Describe the fundamental principles of wireless communications.
- Present suitable models and algorithms for quantifying channel performance over various link conditions.
- Present observations from previous empirical studies on low-power wireless links.

The wireless channel places fundamental limitations on the performance of wireless communication systems. The electromagnetic waves are diffracted, scattered or reflected as the wave propagates through the medium resulting in a decrease in signal strength with distance. The decay in signal strength in respect to distance is known as the path loss index and broadly depends on the environment and frequency of operation [42]. Fading of the signal over certain propagation media may also occur, which will vary with time, geographical position or radio frequency, and is often modelled as a random process. Fading is either due to multipath propagation (referred to as multipath induced fading) or due to shadowing from obstacles affecting the wave propagation (referred to as shadow fading) [43]. The presence of reflectors in the environment surrounding a transmitter and receiver create multiple paths that a transmitted signal can transverse. As a result, the receiver sees a superposition of multiple copies of the transmitted signal, each traversing a different path which can lead to constructive or destructive interference at the receiver [44].

Electromagnetic waves propagating from a transmitter to receiver can be classified as sky waves, space waves and ground waves. Sky waves are reflected from the ionosphere at High Frequency (HF) frequencies (3 to 30 MHz) and can be used for long-range communication. Surface waves, sometimes referred to as ground waves, exist only for vertical polarisation when transmitting and receiving antennas are close to the surface of the earth. For antenna elevations greater than a wavelength above the surface and for frequencies greater 1 MHz, the magnitude of the surface waves becomes negligible [42]. Space waves travel via direct line-of-sight, reflected paths and (sometimes) refracted paths. In this study, the focus is on short-range communications (such as those encountered in WSNs) at microwave frequencies, where only space waves are plausible and of significant influence.

2.2.2 Survey of Channel Models

Multiple link properties, including; path loss, coverage prediction and receiver sensitivity can be analysed using deterministic or statistical approaches. In a deterministic approach, link properties are modelled theoretically using appropriate equations and formula. An example of this is ray tracing, where the possible propagation paths are identified and the amplitude and delay of each path is considered. This approach requires a rich set of information about the environment stored in a three-dimensional database. The process can be time consuming, resource heavy and potentially miss other factors such as interference from adjoining networks and changes to the transmission medium over time. In a statistical approach, mean signal strength, signal quality, packet delivery or other link properties are observed over a range of distances, in different environments and over varying time periods through empirical measurement.

In this work, a combination of deterministic and statistical approaches will be used to analyse properties of the link quality. This will consist of collecting a rich set of empirical data from different WSN environments, under varying conditions and over relatively long time periods. This statistical data will then be compared with theoretical channel models to infer the underlying phenomenon. From this, models that can estimate and predict the optimum TP will be developed.

2.2.3 Relationship between Transmission and Reception Powers

An essential aspect of wireless channel modelling for a TPC protocol is to quantify propagation loss, which defines the relationship between transmission and reception powers. It is dependent on many factors, including; communication distance, carrier frequency and antenna gain. This relationship can be analysed deterministically, under ideal conditions, using the Friis free-space propagation model.

The Friis free-space propagation model is used to estimate the reception power when the transmitter and receiver have a clear, unobstructed, line-of-sight communication path. The model predicts that the reception power (P_r) decays as a function of the transmitter and receiver separation (d), raised to the power two (i.e. a power law function). The signal power at the receiver when considering the transmitter and receiver antenna gains (G_t and G_r, respectively), TP (P_t) and wavelength (λ), can be calculated using Equation 1.

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

Equation 1. *Friis free-space path loss [42].*

The free-space path loss model shows that the received power decays with distance at a rate of 20dB/decade.

Wireless transmission range is defined in terms of transmission loss (L_t) which represents signal attenuation in decibels. It is the difference (in dB) between the transmitted and received signal as described in Equation 2.

$$L_t(dB) = 10\log_{10}(\frac{P_t}{P_r}) = -10\log_{10}(\frac{G_r G_t \lambda^2}{(4\pi)^2 d^2})$$

Equation 2. *Transmission loss [42].*

The equation for unity gain antennas is called path loss (L_p):

$$L_p(dB) = -10\log_{10}(\frac{\lambda^2}{(4\pi)^2 d^2})$$

Equation 3. *Path loss [42].*

Path loss is often expressed as in terms of carrier frequency (f) in MHz and communication distance (d) in metres as shown in Equation 4. $L_p(dB) = 20\log_{10}(f) + 20\log_{10}(d) - 27.56$

Equation 4. *Path loss in standardised form [42].*

The fixed element (-27.56) in Equation 4 is the sum of:

- Converting wavelength (λ) in m to frequency (f) in MHz ($20\log_{10}(300)$
- Simplifying $20\log_{10}(4\pi)$

Different values for the fixed element are required for different units of distance or frequency.

The path loss and transmission loss are related by:

$$L_p(dB) = L_p(dB) - G_t - G_r$$

Equation 5*, Relationship between path loss and transmission loss [42].*

The received power is given by:

$$P_r = P_t - L_t$$

Equation 6. *Received power with respect to transmitted power and transmission loss.*

The Friis free space formula calculates the received power for a distance that is in the far field region of the transmitting antenna. The far field region (d_f) can be calculated from the largest physical dimension of the antenna (D) and the wavelength as follows:

$$d_f = \frac{2D^2}{\lambda}$$

Equation 7. *Far field region [42].*

Since WSNs use radios that operate in the ISM frequency bands (e.g. 433 MHz, 868 MHz, 2.4 GHz, etc.) and incorporate small antennas, the far-field region is close to the transmitting antenna and near-field effects are not often observed. For example, consider the widely used Anaren A1101R08A radio module ([45]), it has an integrated antenna with the largest physical diameter of 17mm. When operating at 868 MHz, the far field region starts at 1.7 mm from the transmitting antenna which is orders of magnitude lower than the typical communication distance.

The free-space path loss model fails to account for fading affects and decay in mean signal strength not caused by free-space, e.g. refraction, diffraction, absorption and reflection. A vast array of works ([7] [9] [20]) have provided empirical characterisations of real-world wireless links and have observed that wireless link quality experiences complex and dynamic tendencies as a result of spatio-temporal factors and hardware inaccuracies. These factors result in large estimation errors when using the free-space path loss model.

Whilst there are many sophisticated deterministic models that can overcome many of the limitations associated with the free-space model (such as Rayleigh, Ricean and Nakagmi distributions [46]), several studies have shown that the log normal shadowing model presented in Equation 8 gives a good match for short-range, line-of-sight communications. The log normal shadowing model incorporates a path loss exponent (α) and a random shadowing term (X_{σ}) to account for the spatio-temporal factors which are often environmentally dependent.

$$L_p(dB) = 10\alpha \log_{10}(f) + 10\alpha \log_{10}(d) - 30\alpha + 32.44 + X_{\sigma}$$

Equation 8. *Path loss for different path loss exponents [47].*

The log normal shadowing model can be further developed to account for more of the factors of the wireless transmission medium. For example, obstacles including walls can be modelled by including additional adsorption terms and the random fading term could be modelled as a multi-dimensional random process to incorporate both temporal and spatial correlations. Even richer models that explicitly characterise the impact of other factors besides distance, e.g. the antenna orientation and height, have been proposed ([42]).

2.2.4 Interference in Wireless Sensor Networks

Interference is a phenomenon inherent to wireless networks because the transmission medium is shared between multiple devices. The dominant co-channel interference in a WSN is likely to be due to the neighbouring nodes (known as internal interference) or due to other wireless equipment operating in the same frequency band (known as external interference). The severity of interference effects are influenced by the network design, e.g. network architecture, MAC protocol, node density and deployment strategy. For example, the co-channel interference experienced in networks with a centralised MAC protocol will be lower than decentralised counterparts because nodes are restricted to transmitting in allocated time slots. Since the network design is application and standard dependent, the aggregate interference experienced by a WSN will often be unique to a single network and liable to change over time. It is therefore difficult to predict the interference experienced in WSNs.

Quantification of aggregate interference experienced by a receiving node in a collaborative network is vital for the performance of upper layer protocols, such as TPC. Interference in WSNs has been studied extensively using both theoretical and empirical approaches in several works ([9] [17] [21]). These works have commonly argued that internal interference is typically minimal and in some cases negligible, even when decentralised MAC protocols are implemented. This is due to the low bandwidth characteristics of the supported applications and the regulatory body restrictions in the ISM bands. For example, the European Telecommunications Standard International (ETSI) impose restrictions on transmission events in the 868 MHz bands which include low duty cycle (< 1% per channel), listen before talk, adaptive frequency hoping and dead time after transmission [48]. External interference, however, has been shown to significantly affect the link quality in WSNs. This is predominantly the result of interference from high TP, high bandwidth, co-habiting networks such as Wi-Fi (IEEE 802.11b) and Bluetooth. It is widely acceptable that for a protocol or mechanism to be applied to multiple applications, the worst-case scenarios (i.e. interference existing in the network) need to be considered.

2.2.5 Noise Floor

The noise floor can be defined as the measure of the signal created from the sum of all the noise sources and unwanted signals within a system which are dependent on hardware, temperature and environment. The noise floor is used to assess the sensitivity of the wireless system, i.e. the minimum possible detectable signal. The noise power (P_n) can be calculated from Boltzmann's constant (k), temperature (T_0) in degrees kelvin, detection bandwidth (B) and the noise figure (F), as shown in Equation 9.

$$P_n = FkT_0B$$

Equation 9. *Noise floor [42].*

The noise power is not fixed and will vary over time depending on the environmental conditions. For example, diurnal temperature changes will influence the thermal noise generated by the radio components [44].

2.2.6 Signal-to-Noise Ratio

The signal-to-noise ratio (SNR) is the degree to which the input signal is greater than the noise power within a bandwidth of interest. The SNR experienced at the receiving node can be estimated from the transmission loss, TP and noise power as follows:

$$SNR = P_t - L_t - P_n$$

Equation 10. *Signal-to-noise ratio [42].*

2.2.7 Bit Error Rate

The bit error rate (BER) for a given radio configuration is a function of the receiver SNR. The exact form of the function depends on the physical layer particulars of the radio, including the modulation technique [49]. The relationship between the theoretical BER and SNR for the most common modulation techniques used in WSNs is shown in Figure 5.

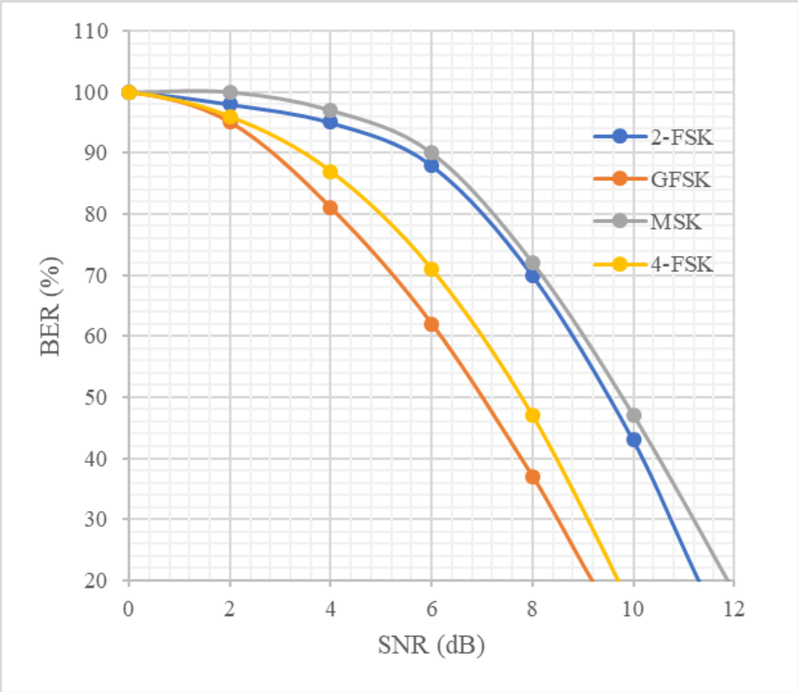


Figure 5. Theoretical BER over SNR for different modulation techniques [50].

Depending on packet size, and any packet-level encoding used, the BER can in turn be used to derive the relationship between packet reception ratio (PRR) and SNR. For example, considering a non-coherent frequency shift keying (FSK) radio, the PRR for a given SNR and packet length (L) can be calculated as follows:

$$PRR = \left(1 - \frac{1}{2} e^{-\frac{SNR}{1.28}}\right)^{L}$$

Equation 11. PRR as a function of SNR and packet length [51].

The relationship between SNR and PRR is of significant importance to a TPC protocol since the TP is typically modulated to achieve the minimum SNR before detrimental effects to the communication reliability occur.

2.2.8 Receiver Sensitivity

The receiver sensitivity is defined as the lowest reception power that yields a packet error rate (PER) less than a predefined figure. The maximum allowable PER is dependent on the standard but many WSN implementations use the guidelines of a 1% PER as defined in IEEE 802.15.4 [52]. Many standards, including IEEE 802.15.4, specify that the receiver sensitivity is based on a best-case noise floor (no interference) and the input signal has perfect modulation accuracy. For example, considering a FSK modulation technique, the carrier frequency offset of the input signal is zero. The effect frequency offset has on receiver sensitivity is shown in Figure 6.

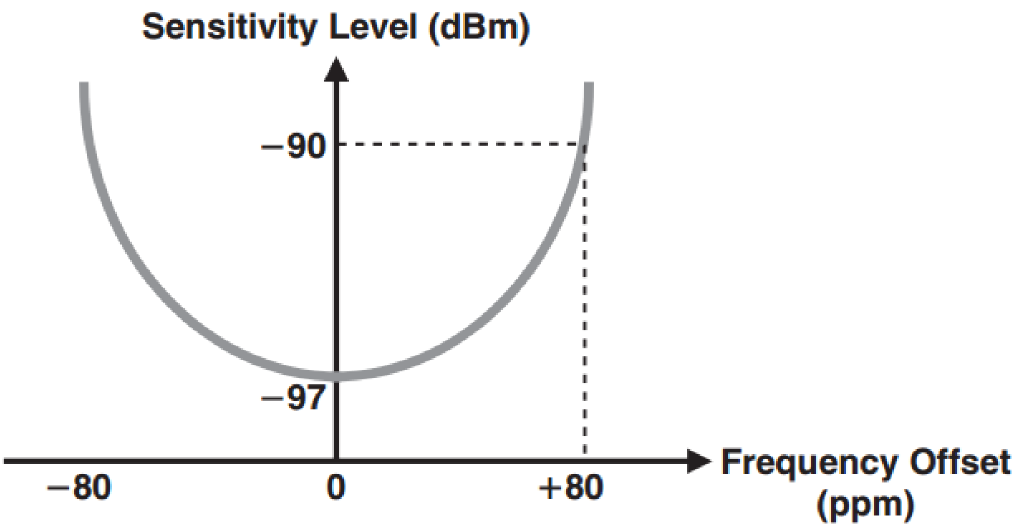


Figure 6. *Receiver sensitivity as function of modulation inaccuracy [53].*

In real-world wireless communication links, signals received at the receiver sensitivity power level are rarely received without errors. This is because:

- **Noise floor**. The noise floor is typically higher than the best-case scenario from which the receiver sensitivity was calculated and is liable to change over time.
- **Modulation inaccuracies**. Shadowing effects, noise and hardware inaccuracies are likely to cause modulation inaccuracies.

Therefore, configuring the TP to a given level which results in the receive signal power being equal to the receiver sensitivity is unlikely to yield optimum performance from both an energy efficiency or communication reliability perspective. Alternative techniques which are able to account for signal variability at the receiver are therefore required.

2.2.9 Empirical Characteristics of Low-Power Wireless Links

Several research efforts have been devoted to an empirical characterisation of low-power wireless links. The observations presented in these works which are most relevant to this thesis are as follows:

- In [7] it was shown that the transmission range is not isotropic, where packets are received within a certain distance. This was attributed to various spatial characteristics, including; irregular antenna radiation pattern, multipath effects and unique propagation paths.
- The effect that obstacles and environmental changes have on link quality was studied in [21] and [54]. The works concluded that link quality will have a complex, unique and dynamic nature in WSN applications so identifying and maintaining the optimum TP is a significant challenge.
- In [18] it was found that links in WSNs are typically asymmetric, i.e. the uplink and downlink properties are significantly different. This observation was confirmed in [12], where the performance difference between the uplink and downlink PRR was as great as 40%.

- The factors which affect link asymmetry was assessed in [55]. This study argued that hardware asymmetry and radio irregularity constitute the major causes of link asymmetry.
- The impact of interference from co-habiting Wi-Fi networks was investigated in [56]. The work found that external interference effects from these networks were severe, leading to performance degradation when a node is operating within 7 MHz of the carrier frequency and within a communication distance of 8 m. In [12] it was noticed that only IEEE 802.15.4 channel 26 is largely immune from this source of interference because it does not overlap with Wi-Fi channels.
- External interference from domestic appliances, such as microwave ovens, was analysed in [57]. Using a spectrum analyser, it was observed that external interference from domestic appliances can spread along several (adjacent) channels, i.e. microwave ovens can cover almost half of the 2.4 GHz available spectrum.
- The importance of interference mitigation for a TPC protocol was shown in [17]. The results highlighted that TPC protocols that do not feature interference mitigation will suffer from poor stability, reliability and energy efficiency in real-world wireless links because of link quality estimation errors.
- The time varying effect on link quality was investigated in [58]. The work highlighted that three typical temporal patterns will exist in WSNs and the severity of each of these will be application dependent.
- Work in [53] (Chapter 2, pages 21-56) compared the theoretical and practical performance of radio hardware. This study argued that theoretical parameters (specified in the datasheet) are often impossible to achieve due to interference, radio hardware inaccuracies and environmental factors.

In the following section the high-level observations from the vast array of empirical studies on low-power wireless links are distilled and classified into spatial and temporal characteristics. Such observations are helpful in the design of an appropriate link quality estimator (LQE) that captures the most important properties of link quality required for a TPC protocol.

2.2.9.1 Spatial Characteristics

Spatial factors include the surrounding environment, such as terrain and the distance between transmitter and receiver. It was demonstrated in several studies ([9] [53] [59]) that the transmission range is not isotropic, where packets are received only within a certain distance from the transmitter. The results presented in [53] are shown graphically in Figure 7.

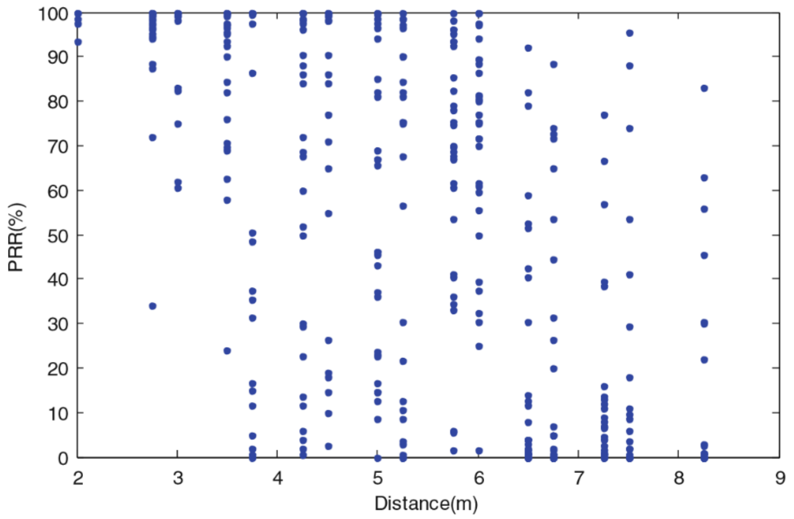


Figure 7. *PRR as a function of communication distance for real-world communication links [53].*

Figure 7 shows that the link quality generally degrades with an increase in communication distance, however this is not always the case. For example, a receiver that is further from the transmitter can have better packet delivery properties than another receiver nearer to the transmitter and two receivers placed at the same distance from the transmitter can have different packet delivery properties. This is due to multiple influences, including:

- **Irregular radiation pattern**. WSNs often use radio modules with on-board low-gain antennas. In such a design, although intended to be omnidirectional, the actual radiation pattern is often irregular. This is mainly the result of circuitry, batteries and metallic housings in close proximity to the antenna which results in the antenna not having the same gain along all propagation directions.
- **Multipath effects**. In instances where the direct signal is weak due to path loss, multipath effects can significantly influence the link quality through constructive or destructive interference.
- **Propagation path**. The decay in signal strength caused by shadowing effects (e.g. refraction, diffraction, absorption and reflection) is unique to a single communication link.

As a result of the spatial characteristics, the relationship between link quality is not deterministic so metrics such as communication distance cannot be used to identify the optimum TP.

2.2.9.2 Temporal Characteristics

Temporal characteristics of the wireless transmission medium change the link quality over time. Several studies ([2] [10] [29]) have confirmed that temporal variations of link quality are due to changes in the operational environment, such as; climatic conditions (e.g. temperature and humidity), human presence, obstacles and interference. As documented by Lin et al. in [58], temporal variations can be categorised into three patterns:

1. **Small fluctuations.** Small fluctuations are the result of multipath fading and changes in temperature and humidity.
2. **Large fluctuations and disturbances.** Large fluctuation and disturbance temporal patterns are typically caused by shadowing and fading effects of humans, moving doors and other objects.
3. **Continuous large fluctuations.** Continuous large fluctuations are the result of interference from high-bandwidth, high TP, co-habiting networks (e.g. adjoining Wi-Fi networks) and appliances operating in the same frequency band (e.g. microwave ovens).

2.2.9.3 Deficiencies with Existing Studies

The aforementioned empirical studies have been carried out using different hardware platforms having different radio ICs, (e.g. MicaZ that incorporates the Chipcon CC2420 used in [2] and [10], whilst the Mica2 with the Chipcon C1000 used in [30] and [35]), different operational environments (e.g. indoor, outdoor) and different experimental settings (e.g. traffic load, channel access mechanism, channel, etc.). They have therefore presented radically different and in some instances, contradictory results on the magnitude of these factors. It is therefore necessary to analyse wireless link quality in typical WSN environments with current state-of-the-art and commonly used radio hardware to draw suitable conclusions upon which a TPC protocol can be designed.

2.2.10 Summary

This sub-section can be summarised as follows:

- Many of the properties that affect wireless link quality are application and environment dependent, and they may be dynamic in nature. For a TPC protocol to identify and maintain the optimum TP, the wireless link quality must be continually evaluated in real-time using statistical approaches and metrics generated internally to the network.
- Deterministic modelling of the network is still required to develop the key principles behind the TPC protocol, such as evaluating the raw link quality metrics. However, deterministic models should be consigned to the development stages as many of the metrics which are required in the computation (such as communication distance, path loss exponent and receiver sensitivity) are unlikely to be known in real-world implementations and are likely to change over time.
- Interference in WSNs is likely in certain applications. This is largely the result of external interference from high-bandwidth, high TP, co-habiting networks (such as Wi-Fi). Internal interference is typically negligible because of the low throughput characteristics of the supported applications and the regulatory body restrictions of the ISM bands. Interference mitigation is therefore a key requirement to ensure energy efficient and reliability operation.

- Real-world communication links are affected by spatio-temporal factors which result in the wireless link quality experiencing complex, unique and dynamic characteristics. Many previous studies have presented contradictory results on the magnitude of these factors in WSN applications. Therefore, further study is proposed to quantify these factors in typical WSN environments and with current state-of-the-art radio hardware.

2.3 Link Quality Estimation

To identify and maintain the optimum TP, the wireless link quality needs to be continually evaluated through a process known as link quality estimation. Link quality estimation consists of evaluating a metric within an estimation window (e.g. at each *w* seconds or based on *w* received/ sent packets) to quantify the quality of a communication link [60]. The generated metric is known as a link quality estimator (LQE). A LQE can estimate the quality on the basis of multiple properties, including; packet delivery, asymmetric, stability, channel quality, channel load and location [61].

Link quality estimation is already used as a fundamental building block in a number of network protocols and mechanisms, such as; medium access control, routing, mobility management, topology control, data rate control and TPC [60]. For instance, routing protocols use link quality estimation to select routes with the best packet delivery properties, whilst data rate control protocols use link quality estimation to evaluate the maximum data rate for an individual communication link. The accuracy, agility and link quality properties captured by the LQE are heavily dependent on the protocol or mechanism it is proposed to be used in and the resources available in the network.

Measuring and characterising link quality in WSNs is a challenging task due to the complex and dynamic nature of transmission medium, the resource limitations of the hardware and the low throughput characteristics of the typical applications. Several simplistic theoretical models were presented in section *2.2 Wireless Channel Modelling* but they were found to lead to gross errors due to spatio-temporal factors of the transmission medium. Although more complex theoretical models were also discussed, these were found to be impractical because their computation required metrics which were generally inaccessible to the transmitting node and they utilised metric evaluation techniques which cannot be implemented on the resource constrained hardware. Therefore, link quality needs to be estimated in real-time, using resources internal to the network and metric evaluation techniques which are practical to implement on the resource constrained hardware.

The remainder of this subsection aims to:

- Describe the link quality estimation process.
- Present the link quality properties that needs to be captured for a TPC protocol.
- Review currently available LQEs.

2.3.1 Link Quality Estimation Process

The link quality estimation process involves three stages as shown in Figure 8.

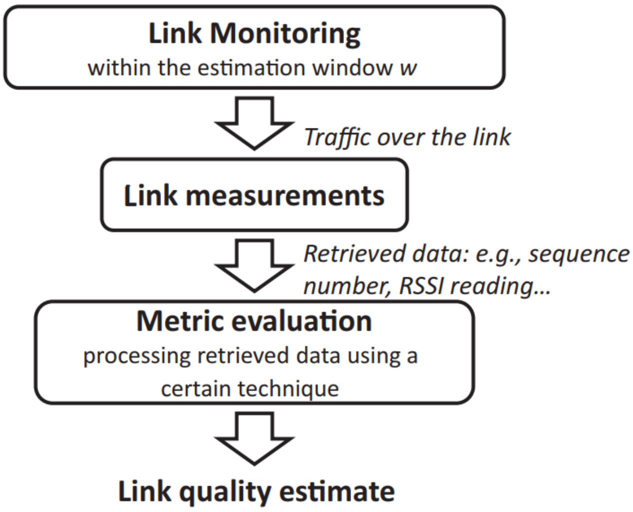


Figure 8. *Link quality estimation process [61].*

Link monitoring defines the strategy to have traffic over the link allowing for link measurements. Baccour et al. in [61] defined three types of link monitoring:

1. **Active link monitoring**. In active link monitoring, a node monitors the links to its neighbours by sending probe packets.
2. **Passive link monitoring**. Passive link monitoring exploits existing traffic without incurring additional communication overhead.
3. **Hybrid link monitoring.** Hybrid mechanisms combine both active and passive link monitoring, allowing a balance between energy efficiency and up-to-date link measurements.

The link monitoring strategy is dependent on the network resources, channel conditions and the sampling requirements of the LQE. Passive link monitoring has been recommended in several previous TPC protocols ([10] [34] [62]) because it has a lower energy overhead than hybrid or active approaches. However, passive link monitoring can lead to a lack of up-to-date link measurements when the network has low throughput so the LQE has to be designed to account for this.

Link measurements can be obtained from metrics captured by received data packets, received acknowledgement packets and transmitted packets. Receiver-side LQEs are computed from metrics retrieved from received data and acknowledgement packets, such as; sequence number, time stamp, receive RSSI, SNR and link quality indicator (LQI). On the other hand, metrics received from transmitted packets, such as; time stamp and packet transmission count, allow for transmitter-side LQEs to be computed. After the link measurements are captured, the raw metrics are evaluated using various estimation techniques, including; averaging, filtering, learning, regression and fuzzy logic.

Each stage of the link quality estimation process needs to be optimised for the requirements of a TPC protocol, the typical network conditions experienced in WSN applications and the resource limitations of the hardware. This includes the use of passive link monitoring and the implementation of simplistic metric evaluation techniques which require minimal memory and computation overhead.

2.3.2 Link Quality Properties

There is wide spread debate on what link quality properties need to be captured to accurately determine the optimum TP. This has led to previous works using a plethora of link quality properties as documented in Table 2 (page 29). In general, the more link quality properties that an LQE can represent, the finer grain link qualification possible and therefore, the higher accuracy achievable in the TPC protocol. However, analysing multiple link quality properties typically requires large amounts of data, collected over large estimation windows. This in turn reduces the agility and increases the computation and memory resources required in the link quality estimation process. It is therefore necessary to only measure the most energy critical properties of the wireless link to ensure the requirements of a TPC protocol can be fulfilled whilst still complying with the resource constraints of WSNs.

Drawing upon observations presented in previous works on wireless channel modelling ([9] [18] [42] [61]), link quality estimation ([8] [29] [59] [60]) and TPC ([17] [29] [36]), multiple link quality properties need to be captured to ensure energy efficient and reliable operation of a TPC protocol. These are described in the subsequent sections.

2.3.2.1 Channel Quality

Channel quality represents properties of the received signal. The most common metrics used to capture channel quality properties relate to the quality of the signal (i.e. Link Quality Indicator, LQI), the power of the received signal (i.e. Receive Signal Strength Indicator, RSSI) and the ratio of the received signal power to the noise power (i.e. Signal-to-Noise Ratio, SNR). Channel quality is of significant importance to a TPC protocol for the following two reasons. Firstly, channel quality properties allow for a quantitative assessment between the configurable parameter, in this instance TP, and the resulting received signal. This relationship needs to be established for a dynamic TPC algorithm to be applied which as described in *2.1.5 Transmission Power Control Algorithms* is more agile than linear and binary approaches and thus allows for greater energy savings. Secondly, channel quality properties allow for a link quality threshold (LQT) to be generated. Many previous works on TPC, including [10] [17] [36], tune the TP to a target value of the channel quality property, commonly referred to as the LQT. Operating at the LQT is predicted to yield the highest energy efficiency, i.e. high probability of successful packet transmission with little excess power at the receiver.

2.3.2.2 Packet Delivery

Packet delivery is the capacity of the link to successfully deliver data and is sometimes referred to as the communication reliability. Packet delivery properties needs to be captured for the following three reasons:

1. **TPC protocols can detrimentally affect communication reliability.** TPC protocols have the potential to detrimentally affect the packet delivery properties of a communication link through using a TPC which does not result in sufficient link budget for successful packet transmission.
2. **Energy considerations**. Communication reliability can significantly affect the energy consumed per transaction due to packet retransmissions [13]. To ensure that communication activities are being carried out at the lowest energy cost (i.e. with no packet retransmissions), the packet delivery properties of the link need to be monitored.
3. **Mitigate against the exposed and hidden node problems**. As identified in [22] and discussed in *2.1.3 Transmission Power Control* Design Considerations, the exposed and hidden node problems can be exacerbated through the implementation of a TPC protocol. The effects of the hidden and exposed node problems can be mitigated through monitoring the packet delivery properties, thus allowing the TP to be increased to leverage the capture effect or to bring the interfering transmitter within the carrier sense range.

2.3.2.3 Channel Stability

Channel stability is a measure of the variability level of the link. As LQEs are calculated based on historic performance of the network (over a prior estimation window), when they are used (during the operational window) they may not be representative of the current channel conditions due to link quality changes between the two windows. Channel stability metrics give a measure of how similar the performance of the network is likely to be over the operational window compared to the estimation window.

As discussed in [29], capturing channel stability properties is of significant importance to a TPC protocol because they allow for an adaptive fade margin to be implemented. For links with low variance (and hence high stability), the perceived performance of the network is likely to be fairly similar in the estimation and operational windows so the LQE should be a good representation of the actual channel conditions. This subsequently allows a small fade margin to be implemented (i.e. target TP ≈ calculated optimal TP) without significant risk of detrimental effects on communication reliability and energy usage (due to packet retransmissions). Conversely, communication links with high variance (poor stability) result in the LQE not being a close account of current channel conditions so a larger fade margin is required to reduce the risk of performance degradation.

Other link properties, such as packet asymmetry and channel load, are of less relevance to a TPC protocol because they do not represent the characteristics of WSNs or the requirements of the application. For instance, packet asymmetry can be ignored because communications in WSNs are typically one way (upstream) from node to sink and the sink will have significantly higher energy resources so optimising the downstream link is not as critical. Measuring only the properties of the link quality which are most relevant to the proposed application increases the agility and reduces the memory and computation resources required for the link quality estimation process.

2.3.3 Link Quality Estimators

Several LQEs have been reported in the literature. They can be classified as either hardware or software based, as shown in Figure 9.

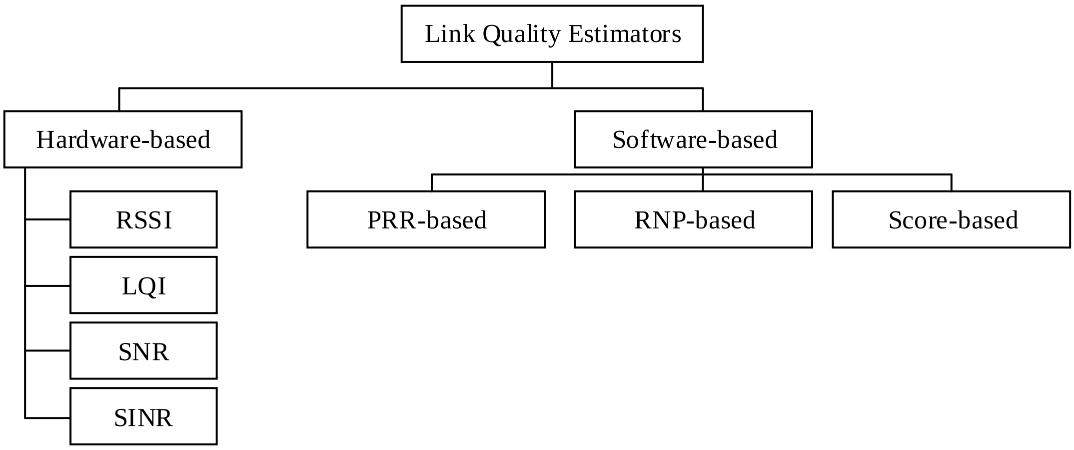


Figure 9. *Taxonomy of link quality estimators [61].*

2.3.3.1 Hardware Link Quality Estimators

Hardware-based LQEs have been extensively used to assess the channel quality properties of communication links in WSNs applications. Their main advantage is that they require very minimal, and in some instances no post processing so can provide a fast and inexpensive method (from a computation and memory perspective) of evaluating link quality. The most common hardware-based LQEs are:

- **RSSI**. RSSI is an estimate of the received signal power in the transmission channel [52]. It is the RF power input to the receiver (denoted as P_r in Figure 1) and can be expressed as:

$$RSSI = P_s + P_i + P_n$$

$$P_i = \sum_{m-1}^{M} P_{i_m}$$

Equation 12. *Receive signal strength indicator [17].*

  Where; P_s, P_i and P_n are the signal, interference and noise power, respectively and P_{i_m} is the interference power from interference number m and M is the total number of interferers. RSSI is not typically monitored over the complete packet and is often estimated over the preamble [8] (e.g. the first 16-bits for the Texas Instrument CC1101 chipset [63]).

- **LQI**. LQI is a measure of the modulation quality of the received signal and can be calculated based on receiver energy detection, SNR estimation, or a combination of these metrics [17] [63]. Although LQI has been proposed in IEEE 802.15.4 (the most common MAC/PHY layer standard used in WSNs [1]), no definitive explanation of its measurement range or calculation is given [17]. Texas Instruments, a leading chipset manufacture for low-power radios, define

LQI as a metric that quantifies the error in the modulation parameter (frequency for FSK and GFSK, phase for MSK, amplitude for ASK) against the ideal constellation. Other chip manufactures calculate LQI using slightly different methods so it is therefore a manufacture specific metric.

- **Signal-to-interference-and-noise ratio (SINR).** SINR is the ratio of the power of the signal, to the interference plus noise power. It is expressed as:

$$SINR = P_s - (P_n + P_i)$$

Equation 13. *Signal-to-interference-and-noise ratio [17].*

On platforms that do not feature an SINR register, this metric can be estimated through reading the RSSI register during packet transmission to estimate P_s and just after to estimate $P_n + P_i$.

- **SNR**. SNR is the ratio of the power of the signal, to the background noise. It is expressed as:

$$SNR = P_s - P_n$$

Equation 14. *Signal-to- noise ratio [17].*

Similar to SINR, SNR can be estimated through reading the RSSI register during packet transmission to estimate P_s and sometime after, when the channel is clear, to estimate P_n. To identify when the channel is clear (i.e. no transmissions and interference effects are negligible), clear channel assessment (CCA) modes are required. Although CCA modes are required to be compliant with IEEE 802.15.4 [52], they are not a common feature of all wireless standards used in WSNs. This means that identifying when the channel is clear is sometimes impossible so estimating SNR can be particularly challenging.

2.3.3.2 Software Link Quality Estimators

Software-based LQEs are derived through packet statistics collection (e.g. packet sequence number). Software-based LQEs can be classified into three categories (as shown in Figure 9):

- **Packet reception ratio (PRR)**. PRR-based LQEs represent the ratio of the number of successfully received packets (N_{rx}), to the number of transmitted packets (N_{tx}) over a sampling window (w), as shown in Equation 15. The sampling window typically represents a fixed number of packets or a fixed time period.

$$PRR = \frac{N_{rx}}{N_{tx}}$$

Equation 15. *Packet reception ratio [53].*

PRR is simple to measure but its efficiency is dependent on the estimation window size. In [64] it was shown that for links with very high or very low PRRs, accurate link quality estimation can be achieved over small sampling windows. On the other hand, links with medium PRRs need much larger sampling windows to converge to an accurate link quality estimate which in turn increases the memory and computation overhead. The objective of LQEs that approximate PRR, such as Window Mean with Exponentially Weighted Moving Average (WMEWMA) [65] and Kalmann Filter (KLE) [66], is to provide more efficient link quality estimates than the PRR.

- **Required number of packet retransmissions (RNP)**. RNP-based LQEs count the number of packet retransmissions (N_{rtx}) required before a successful packet reception is detected, as shown in Equation 16.

$$RNP = \frac{N_{tx} + N_{rtx}}{N_{rx}} - 1$$

Equation 16. *Required number of packet retransmissions [53].*

- **Score**. Score-based LQEs provide a link estimate that does not refer to a physical phenomenon (like packet reception or packet retransmissions); rather they provide a score or a label that is defined within a certain range [53].

2.3.4 Comparison of Link Quality Estimators

Several previous studies ([53] [61]) have acknowledged that comparing the performance of currently available LQEs is a challenging task. This is because there is a lack of ground-truth metric upon which the accuracy of different estimators can be compared. In classic estimation theory, an estimation process can be compared to a real known process using a certain statistical tool (e.g. least mean square error). However, such comparison is not possible in link quality estimation since there is no metric that is considered the "real" one as link quality is represented by quantities of different natures.

A table (Table 3) has been formulated to show the high-level characteristics of currently available LQEs. From Table 3 it can be seen that many of the currently available LQEs only capture single link properties so can only provide partial characterisation of the communication link. For example, all PRR and RNP based software LQEs are only able to account for the packet delivery properties of the communication link. This is a result of them being primarily designed for routing protocols, where link quality estimation is used to identify the links with the best packet delivery properties to ensure reliable communication. As discussed in *2.3.2 Link Quality Properties*, analysis of previous works highlights that multiple link properties (namely; channel quality, packet delivery and channel stability) need to be captured for a TPC protocol to ensure energy efficient and reliable operation. This renders these single property LQEs unsuitable for a TPC protocol in their current form.

From Table 3, none of the currently available LQEs target all the properties which are proposed for a TPC protocol. The channel state information (CSI) [67] LQE can account for channel quality and packet delivery properties but is unable to account for stability properties of link quality. CSI also uses active link monitoring, which as discussed in *2.3.1 Link Quality Estimation Process*, does not exploit existing network traffic so requires extra communication and energy overhead. The fuzzy link quality estimator (F-LQE) is able to account for all the proposed link quality properties for a TPC protocol, as well as, channel asymmetry. However, as documented in [60], F-LQE requires significant memory and computation resources as it captures four different metrics and uses a complex metric evaluation technique (fuzzy logic). It is therefore not practical to implement on the resource constrained hardware.

From the above analysis, it can be seen that a new LQE needs to be designed for the proposed TPC protocol that captures the link quality properties which are required to ensure energy efficient and reliable operation, whilst still being practical to implement on the resource constrained hardware.

Type	Link quality estimator	Link quality properties captured					Technique	Link monitoring	Location
		Channel quality	Packet delivery	Channel stability	Asymmetry	Other			
Hardware	RSSI [63]	X					Read from hardware and can be averaged	Passive or active	Receiver
Hardware	LQI [63]	X							
Hardware	SNR [17]	X							
Hardware	SINR [17]	X							
Software, PRR	PRR [61]		X				Average	Passive or active	Receiver
Software, PRR	WMEWMA [65]		X				Filtering	Passive	Receiver
Software, PRR	KLE [66]		X				Filtering	Not explicit	Receiver
Software, RNP	RNP [53]		X				Average	Passive	Sender
Software, RNP	Expected Transmission Count (ETX) [68]		X				Average	Active	Receiver
Software, RNP	Four-bit [69]		X				Filtering	Hybrid	Sender and receiver
Software, RNP	Link Inefficiency (LI) [70]		X				Probability	Passive	Receiver
Software, RNP	Link Expected Transmission Count (L-ETX) [71]		X				Filtering	Active	Sender
Software, score based	Fuzzy link quality estimator (F-LQE) [60]	X	X	X	X		Fuzzy logic	Passive	Receiver
Software, score based	Weighted Regression Estimator (WRE) [7]	X				Location	Regression	Passive	Receiver
Software, score based	MetricMap [72]	X				Channel load	Training and classification	Passive	Receiver
Software, score based	Channel State Information (CSI) [67]	X	X		X		Weighted sum	Active	Receiver

Table 3. *Taxonomy of currently available link quality estimators.*

2.3.5 Summary

This sub-section can be summarised as follows:

- A LQE is required to assess the quality of the communication link in order to identify and maintain the optimum TP. To account for the dynamic link conditions, the link quality needs to be estimated in real-time, using resources internal to the network and metric evaluation technique which are practical to implement on the resource constrained hardware.
- The estimation process has three stages (monitor, measure and evaluate) and each stage needs to be optimised for the application. This includes the use of passive link monitoring and metric evaluation techniques which are practical to implement and can account for the lack of up-to-date information.
- The link quality properties captured by the LQE are application dependent. TPC protocols require channel quality, packet delivery and channel stability properties to be captured to ensure energy efficient and reliable operation.
- Comparing the properties captured by currently available LQEs against the requirements of a TPC protocol, there is a need to design a new LQE that is tailored to the requirements of TPC protocols for WSN applications.

Chapter Three: Radio Energy Considerations

3.1 Introduction

Although transmission power control (TPC) has been studied extensively in the literature, there is a lack of ground-truth about the potential energy savings achievable through its implementation. This is because previous works have produced radically different results about the maximum energy savings of their respective protocols. For example, in [10] energy savings of up to 79% were reported, whilst in [35] it was concluded that this was only 27% despite both protocols operating in similar ways. The vastly different results are due to studies being carried out using different hardware platforms having different radio ICs, different operational environments and different experimental settings.

Second to this, the energy consumed to transmit a bit of data (E_{bit}) can be decomposed into distance dependent and distance independent parts. Observations by Chandrakasan et al. in [73] highlighted that the distance independent term of E_{bit} dominates the distance dependent term at short communication distances, such as those found in wireless sensor networks (WSNs). This has led to the assumption that protocols and mechanisms, such as TPC, that target the distance dependent term not presenting significant opportunities to reduce the energy consumed by wireless communication activities in WSNs.

To address the lack of ground-truth about the potential energy savings of a TPC protocol, a mathematical model that compares transmission power (TP) against communication reliability and energy consumption is developed. Applying this models to state-of-the-art radio hardware, the maximum potential energy savings are quantified and the link conditions which offer the greatest energy savings are identified.

3.2 HCB Energy Model

To quantify the energy dissipated by transmitting and receiving radios (E_{tx} and E_{rx} , respectively), the first order Heinselman-Chandrakasan-Balakrishnan (HCB) energy model [74] is deployed. The HCB model calculates the nominal energy dissipated by both transmitting and receiving radios through a computation taking into account the energy dissipated by transmitter/ receiver electronics (E_{elec}), energy dissipated by the transmit amplifier (ε_{amp}), packet length (k) in bits, communication distance (d) and path loss exponent (α). A block diagram of the HCB model is shown in Figure 10, with the algebraic expressions shown in Equation 17 and Equation 18.

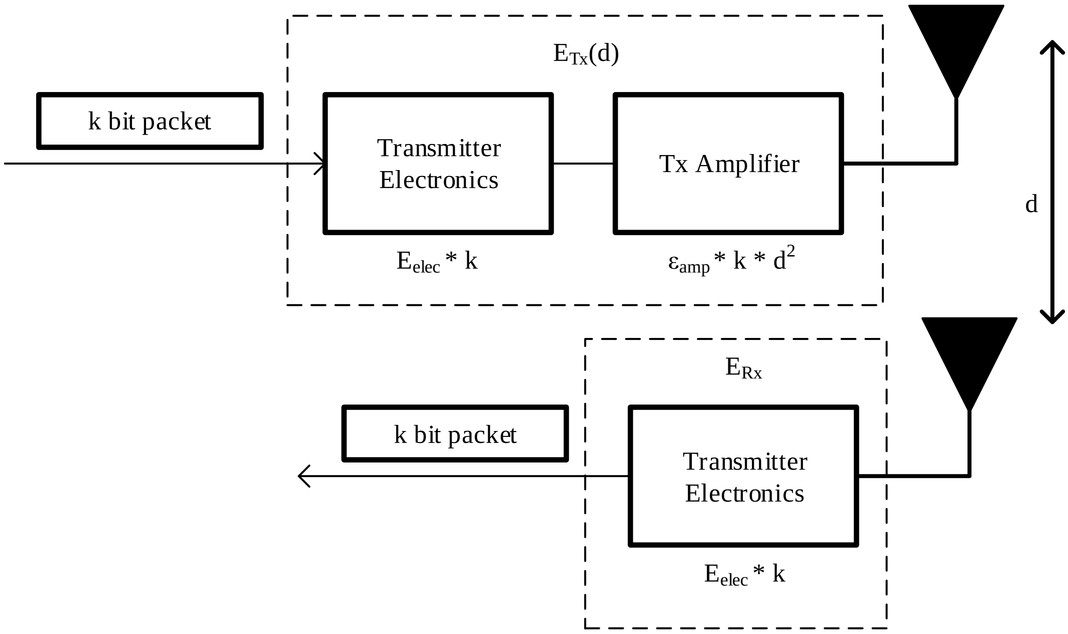


Figure 10. *First order HCB energy model [74].*

$$E_{tx}(k,d) = E_{elec}k + \varepsilon_{amp}kd^{\alpha}$$

Equation 17. *Energy dissipated by transmitting radio [74].*

$$E_{rx}(k) = E_{elec}k$$

Equation 18. *Energy dissipated by receiving radio [74].*

For this study, the following parameter values are used.

Parameter	**Value**	**Units**
E_{elec}	50	nJ/bit
ε_{amp}	0.1	nJ/bit/m^2

Table 4. *Parameters for HCB model.*

These parameters are in line with state-of-the-art radio design. For example, it is assumed that the radio dissipated 50 nJ/bit to run the transmitter and receiver circuitry (E_{elec}). This is similar to the performance of the Nordic Semiconductor nRF2401 radio transceiver (1 Mbps data rate radio that operates at 2.7 V and consumes 16.8 mA of current [75]) which has been extensively used in previous WSNs (e.g. Tyndall Mote [76] and Hogthrob [77]).

Assuming link layer acknowledgement and retransmission schemes are implemented, the energy dissipated per transaction (E_{trans}), assuming acknowledgement packets are always successfully received, is given by:

$$E_{trans} = N_{tx}(E_{tx} + E_{rx})$$

Equation 19. *Energy dissipated per transaction [74].*

The number of packet transmissions (N_{tx}) required before a high probability of successful packet reception can be calculated using Equation 20, where P_a is the confidence interval (probability that after n transmissions the packet will be successfully received, typically 99%), PRR is the packet reception ratio (probability that a single packet will be successfully received) and ln is the natural log

$$N_{tx} = \frac{\ln(1 - P_a)}{\ln(1 - PRR)} + 1$$

Equation 20. *Number of packet transmissions before successful packet reception.*

Link layer protocols typically place limits on the maximum number of transmissions ($N_{tx\_\max}$). In this study it is assumed that $N_{tx\_\max} = 3$ which is in line with link layer protocols typically used in WSNs, such as WirelessHART [15] and Bluetooth low energy [14]. The first order HCB model equations (Equation 17 and Equation 18) can be made packet length agnostic by dividing through by k. The energy dissipated per bit (E_{bit}) is therefore:

$$E_{bit} = \frac{N_{tx}(E_{tx} + E_{rx})}{k}$$
$$E_{bit} = N_{tx}(E_{elec} + (E_{elec} + \varepsilon_{amp} d^{\alpha}))$$
$$E_{bit} = N_{tx}(2E_{elec} + \varepsilon_{amp} d^{\alpha})$$

Equation 21. *Energy dissipated per bit.*

3.3 Generalised Energy Model

In order to evaluate E_{bit} when different TPs are considered, Equation 21 needs to be modified to represent the actual, rather than the nominal, energy dissipated. As shown in Equation 22, this can be achieved by substituting $\varepsilon_{amp} d^{\alpha}$ with E_{tpx} (energy dissipated by the transmitter power amplifier when different TPs are considered).

$$E_{bit} = N_{tx}(2E_{elec} + E_{tpx})$$

Equation 22. *Energy dissipated per bit when different transmission power levels are considered [74].*

Combining E_{bit} when different TPs are considered (Equation 22) with path loss (L_P) (Equation 8), signal-to-noise ratio (SNR) (Equation 10) and packet reception ratio (PRR) (Equation 11), a generalised model showing the relationship between TP (P_t), communication reliability and E_{bit} for an arbitrary communication distance, path loss exponent and carrier frequency (F) can be created. This model is represented algebraically in Equation 23 and Equation 24, and shown graphically in Figure 11 for a representative WSN communication link (Texas Instrument CC1101 radio operating over a communication distance of 20 m with a path loss exponent of 2).

$$PRR = (1 - \frac{1}{2} e^{\frac{P_t - P_n - L_p}{1.28}})^{8k}$$

Equation 23. *Packet reception ratio as a function of transmission power, path loss and background noise.*

$$E_{bit} = (\frac{\ln(1 - P_a)}{\ln(1 - PRR)} + 1) \times (2E_{elec} + E_{tpx})$$

Equation 24*, Energy dissipated per bit as a function of packet reception ratio, confidence interval and energy dissipated by the transmitter amplifier when different TP are considered.*

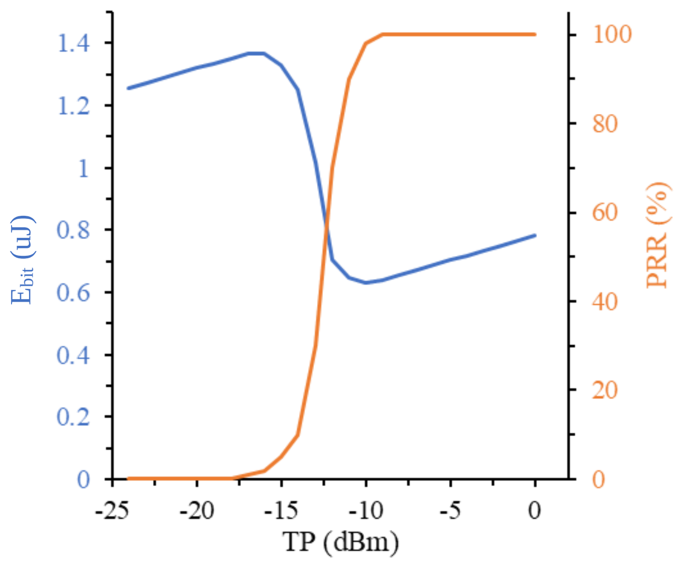


Figure 11. *Relationship between TP, communication reliability and E_{bit} [13].*

3.4 Potential Energy Savings

As seen in Figure 11, the TP that results in the minimum value of E_{bit} exists on the boundary between the connected and transitional regions. At the optimum TP, packets are sent with just enough energy to ensure successful packet reception at the receiver with a low probability of a bit error. Figure 11 shows that it is preferable to use a slightly higher, rather than lower, TP because E_{bit} increases much more rapidly and communication reliability is detrimentally affected when the TP is below the optimum level.

Using the generalised model, the maximum potential energy savings that can be achieved through the implementation of a TPC protocol can be quantified. The maximum energy savings are dependent upon which connectivity region the link belongs to. For links that exist in the connected region, energy savings can be achieved through lowering the TP, thus ensuring that packets are not sent with excessive power for the intended recipient. Referring this observation to Equation 22, links in the connected region can only be improved by reducing the E_{tpx} term, since E_{elec} is fixed and N_{tx} is close to its minimum value (i.e. $N_{tx} \approx 1$) because the communication reliability is nearly perfect (i.e. PRR > 95%). Therefore, the maximum energy savings achievable in the connected region ($E_{conn\_\max}$) is the difference in E_{bit} between using the minimum ($E_{tp\_\min}$) and maximum ($E_{tp\_\max}$) TP, as follows:

$$E_{bit\_\min} = 2E_{elec} + E_{tp\_\min}$$
$$E_{bit\_\max} = 2E_{elec} + E_{tp\_\max}$$
$$E_{conn\_\max} = \frac{E_{tp\_\max} - E_{tp\_\min}}{E_{tp\_\max}}$$

Equation 25. *Maximum energy savings in connected region.*

The maximum energy savings in the connected region are radio hardware dependent since the following parameters vary between devices: TP range, power amplifier efficiency and E_{elec}. Values of $E_{conn\_\max}$ for state-of-the-art radio hardware commonly used in WSNs varies between 38-80% as calculated from the datasheet parameters presented in *Appendix 1: Taxonomy of state-of-the-art radio hardware commonly used in WSNs*.

Communication links that exist in the transitional and disconnected regions can be improved from energy efficiency and communication reliability perspectives through increasing the TP. In these regions, E_{bit} is dominated by N_{tx} as the difference in TP that results in a link residing in the connected or disconnected regions is minimal (e.g. E_{tp_conn} is typically only 10% greater than E_{tp_disc}). This results in the maximum energy savings being largely influenced by $N_{tx\_\max}$ as shown in Equation 26.

$$E_{bit\_conn} = N_{tx\_\min}(2E_{elec} + E_{tp\_conn})$$
$$E_{bit\_disc} = N_{tx\_\max}(2E_{elec} + E_{tp\_disc})$$
$$E_{tp\_conn} \approx E_{tp\_disc}$$
$$E_{disc\_\max} = \frac{N_{tx\_\max} - N_{tx\_\min}}{N_{tx\_\max}}$$

Equation 26. *Maximum energy savings in the disconnected region.*

As an example, most current WSN standards specify that $N_{tx\_\max}$ is 3 so the maximum energy savings achievable in the disconnected region can be quantified to be around 66%.

3.5 Relationship between Channel Conditions and Energy Savings

As highlighted in [74], E_{bit} (Equation 21) calculated from the first order HCB model consists of distance dependent and distance independent terms, $2E_{elec}$ and $\varepsilon_{amp}d^{\alpha}$ respectively. Chandrakasan et al. in [73] concluded that for many short-range radios, the distance dependent term typically dominates (i.e. $2E_{elec}$ > $\varepsilon_{amp}d^{\alpha}$). To observe this characteristic, the dominance of the distance dependent (d_{dep}) term on E_{bit} over varying communication distances and for different path loss exponents was analysed, with the results presented in Figure 12.

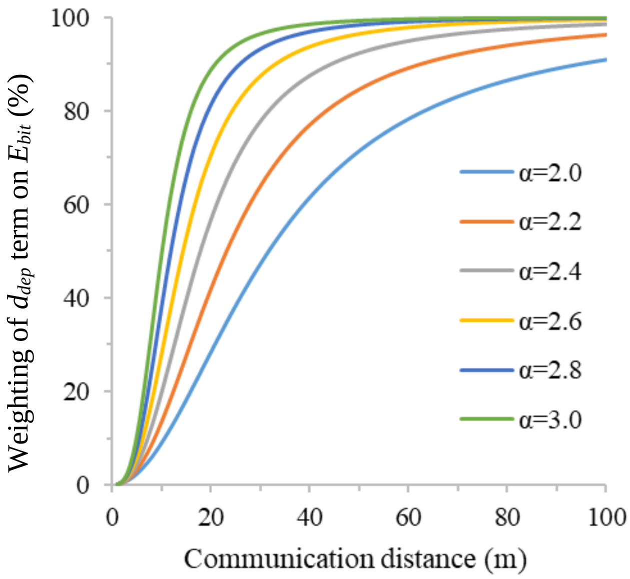


Figure 12. *Weighting of distance dependent (d_{dep}) term on E_{bit} for varying communication distance and path loss exponent.*

As seen in Figure 12, the dominance of the distance dependent term is a factor of the communication distance and path loss exponent. Under ideal conditions, assuming only propagation losses are the result of free-space propagation (α = 2), the distance dependent term only becomes of significant influence (i.e. the distance dependent term accounts for over 50% of E_{bit}) when the communication distance is greater than 30 m. Below this, E_{bit} is dominated by the distance independent term. When considering real world communication links, where propagation losses due to shadowing, reflection and diffraction are likely to occur (i.e. α > 2), the communication distance at which the distance dependent term becomes of significant influence is lower. For example, considering an office environment where α = 3 [53], the distance dependent term becomes of significant influence when the communication distance is 10 m. This model suggests that protocols and mechanisms that aim to reduce E_{bit} through targeting the distance dependent term may not offer significant energy savings for short communication distances and methods of improving circuit efficiency (e.g. higher data rate, low supply voltage, lower current consumption) as suggested in [73], would offer more greater opportunities.

However, the HCB model calculates the nominal energy dissipated so its results are based upon using the nominal TP. To identify and maintain the nominal TP, a TPC protocol is required. Many current WSN standards (such as WirelessHART [15] and Bluetooth Low Energy [14]) use a fixed TP so are unable to benefit from the fact that E_{bit} can be minimised based on current channel conditions. As current WSN standards typically fix the TP to the maximum level, the distance dependent term will be fixed at its maximum value (Emax). The energy savings achievable through using the optimum TP, rather than the maximum, for different channel conditions (communication distances and path loss exponents) are shown by the green shaded areas in Figure 13. Note the results in Figure 13 are based on the performance metrics of the Nordic nRF2401 ([78]) but other radio hardware will exhibit similar characteristics.

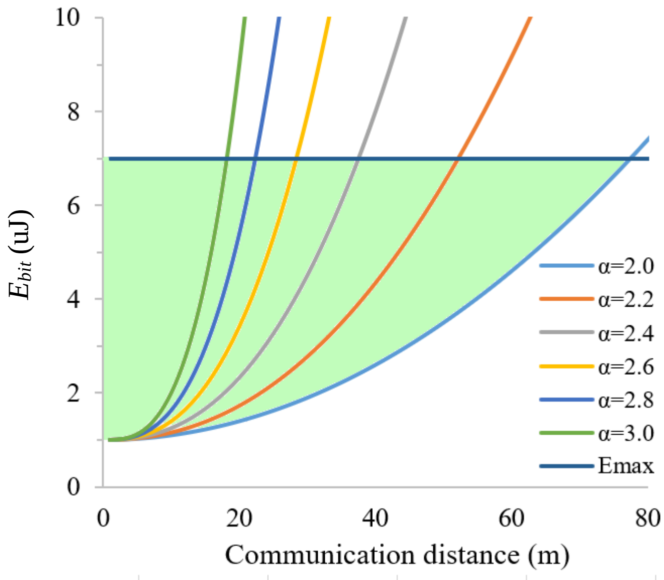


Figure 13. *Potential energy savings through using the optimum transmission power.*

As seen in Figure 13, the potential energy savings are dependent on the communication distance and path loss exponent. For example, when α=2.0 and the communication distance is 40m, E_{bit} = 2.0uJ when the optimal TP is used. This represents a 71% energy saving when compared to the link performance when the maximum TP is used. As seen by the green shaded area, the energy savings are lower when the path loss exponent and/ or communication distance increase. For example, when α=2.4 and the communication distance is 30m, E_{bit} = 4.0uJ when the optimal TP is used and this only represents a 42% energy saving. This highlights that the maximum energy savings are achievable under ideal channel conditions and at short communication distances. This observation disproves previous assumptions about the limited impact of protocol and mechanisms that target the distance dependent term not offering significant energy savings at short communication distances.

3.6 Summary

In this chapter, a mathematic model that compares TP against communication reliability and energy consumption has been developed. From this, the potential energy savings achievable through the implementation of a TPC protocol have been quantified. The results show that optimising the TP can significantly reduce the energy consumed by wireless communication activities for links that exist in the connected, transitional and disconnected regions. Using performance metrics from commonly used, state-of-the-art radio hardware and parameter values from current WSN standards, this study highlights that energy savings of up to 38-80% are achievable for links that belong to the connected region and up to 66% for links that belong to the disconnected region.

On top of this, previous assumptions that protocols and mechanisms that target the distance dependent term of E_{bit} not being able to achieve significant energy savings at short communication distances have been contested. This work has shown that the greatest energy savings are achievable at short communication distances and under ideal channel conditions.

As seen in this study, the energy consumed by communication activities are heavily influenced by the radio hardware and environment. Comparing link performance when TPC is applied against when the maximum TP is used (as has been used in other works [2] [10] [79]) is therefore a poor evaluation metric. An alternative evaluation process, such as comparing the link performance against an offline computation of the optimum link performance, is therefore recommended.

Chapter Four: Empirical Study of Link Quality Assessment in Wireless Sensor Networks

4.1 Introduction

In this chapter, an empirical characterisation of low power wireless links in typical wireless sensor network (WSN) environments is presented. The purpose of this study is to identify and quantify the spatial and temporal factors present in typical WSN environments, describe the in-situ correlation between transmission power (TP) and link quality, as well as provide meta-data for the overarching design of a transmission power control (TPC) protocol.

Several previous research works ([9] [10] [21]) have presented empirical characterisations of low-power wireless links. These works commonly argue that link quality exhibits complex and dynamic tendencies as a result of spatial and temporal factors. The spatial factors include the surrounding environment, such as terrain and the communication distance. Temporal variations of link quality are due to changes in the operational environment, such as; climatic conditions, human presence, obstacles and interference. As discussed in *2.2.9 Empirical Characteristics of Low-Power Wireless Links*, previous empirical studies have produced contradictory results on the magnitude of the spatial and temporal effects and have not focused on radio and link dynamics in the context of different TP settings. It is therefore necessary to analyse these factors in real-world WSNs and with state-of-the-art radio hardware to identify and quantify the typical sources of link degradation that TPC protocols will encounter.

4.2 Experimental Methodology

To assess link quality, the receive signal strength indicator (RSSI) metric was used. As described in *2.3.3.1 Hardware Link Quality Estimators*, RSSI is a measurement of the RF power input to the receiver and it is typically estimated over the preamble. To generate this metric, an experimental WSN was created. The network consisted of several nodes connected to a sink using a single hop, star network topology. Both the node and sink use the Anaren A1101R08A radio module which is based on the Texas Instrument CC1101 IC. This module was chosen because it has a large TP range (-30 to 12 dBm), good TP granularity (total of 32 levels), allows for easy retrieval of link quality metrics and closely represents the performance of state-of-the-art radio hardware commonly used in WSN (as seen in *Appendix 1: Taxonomy of state-of-the-art radio hardware commonly used in WSNs*) [45].

The basic operation of the experimental WSN is presented in Figure 14. The node and sink are placed 0.5 m above the ground at different locations, maintaining the same antenna direction. The node sends out 100 beacon packets (at a rate of 500 packet per second) at each TP level. The generated link metrics, which are retrieved from beacon acknowledgement packets, are saved in non-volatile memory on the node and subsequently downloaded and analysed after the test is complete. To obtain statistical confidence, multiple measurements were taken for each test condition and the experiments were repeated with three different sets of wireless hardware (node/ sink pairs) to ensure hardware variance and calibration didn’t significantly affect the result.

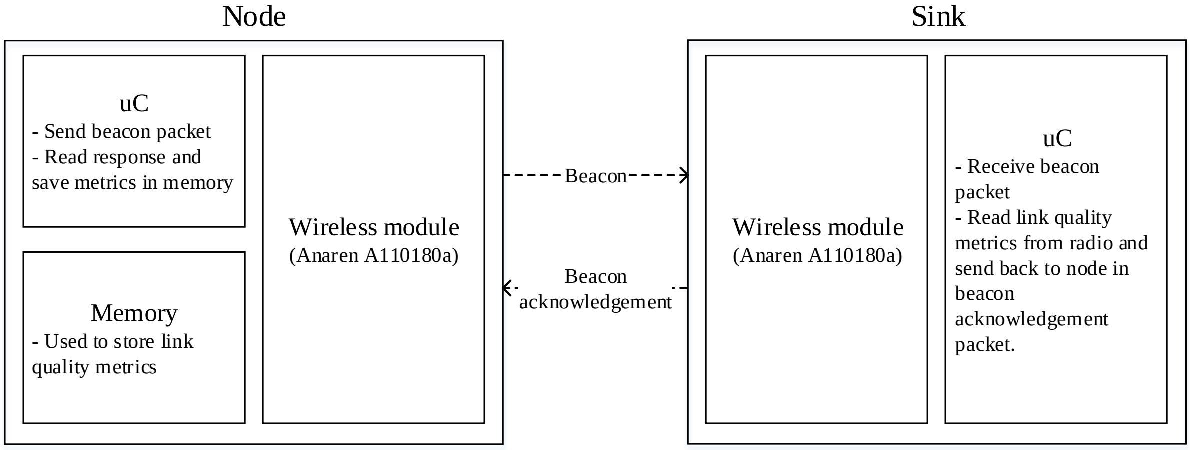


***Figure 14**. Experimental WSN block diagram.*

To compare link quality at different TP levels, simultaneous measurements should ideally be taken at all TP levels, however, this is infeasible in practise. This is because configuring the TP takes a finite time period (e.g. 10ms for the Texas Instrument CC1101 [63]). As an approximation, packets were transmitted in quick succession at different TP levels to minimise the risk of temporal factors affecting the transmission medium over the measurement window.

4.3 Spatial Characteristics

To assess and quantify the spatial impact, a study into the correlation between path loss and communication distance was carried out in three environments which are representative of WSNs. The test environments were chosen to be a grass field (Figure 15a), an office (Figure 15b) and a warehouse (Figure 15c), to represent WSN environments in a range of applications, including; smart energy, environmental monitoring and industrial automation. Path loss as described in Equation 6, is the difference between transmitted and received powers. It can be estimated through comparing the captured RSSI metrics against the TP setting. The relationship between RSSI and TP is generally monotonic and continuous over short time periods and the relationship can be estimated as linear as seen in Figure 16. However, the relationship is not deterministic as it is influenced by several factors, including; hardware inaccuracies, propagation path, accuracy of RSSI readout and antenna orientation. For the analysis, the path loss was averaged over the complete TP range to minimise measurement errors.

***Figure 15**. Test environments a) grass field, b) office, c) warehouse.*

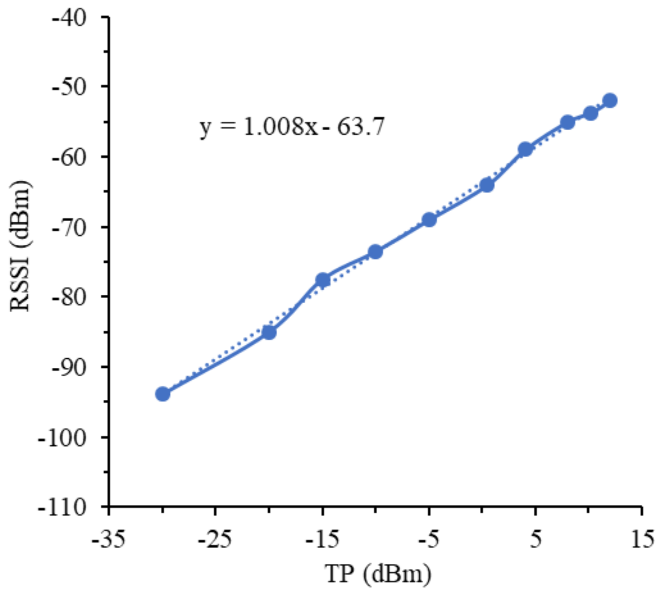


***Figure 16**. RSSI against TP.*

The results from one node/ sink pair in the three test environments are shown in Figure 17. The results from different node/ sink pairs showed similar characteristics and variations so to simplify the analysis, the results from these pairs are not presented in this chapter. The confidence intervals (97%) were calculated to show the variance in the measured parameter over the measurement window. However, due to the stable performance of RSSI, the confidence intervals were negligible so they have not been included in Figure 17.

The results can be summarised as follows:

1. **An increase in communication distance does not always result in an increase in path loss**. As per the Friis free-space path loss model (Equation 1), the received power decays as a function of the communication distance, raised to the power two (i.e. a power law function) so the path loss should increase with distance. The results show that the path loss generally increases as the communication distance increases, but this is not always the case. For example, the path loss in the office environment was 2 dB lower at communication distance of 19 m compared to that at 13 m. This is believed to be caused by multipath effects, as a result of the electromagnetic waves being reflected, diffracted and scattered as the wave propagates through the medium. This results in the receiver seeing a superposition of multiple copies of the transmitted signal that leads to constructive or destructive interference at the receiver depending upon the nature of the propagation path.
2. **The relationship between communication distance and path loss is environmentally dependent**. The relationship between path loss and communication distance is significantly different for the three test environments. For example, at a communication distance of 3 m, the path loss was 54.1 dB in a grass field environment, 65.2 dB in an office environment and 55.0 dB in a warehouse environment. This is the result of the different environments presenting unique sets of propagation paths which attenuate the signal in vastly different ways.

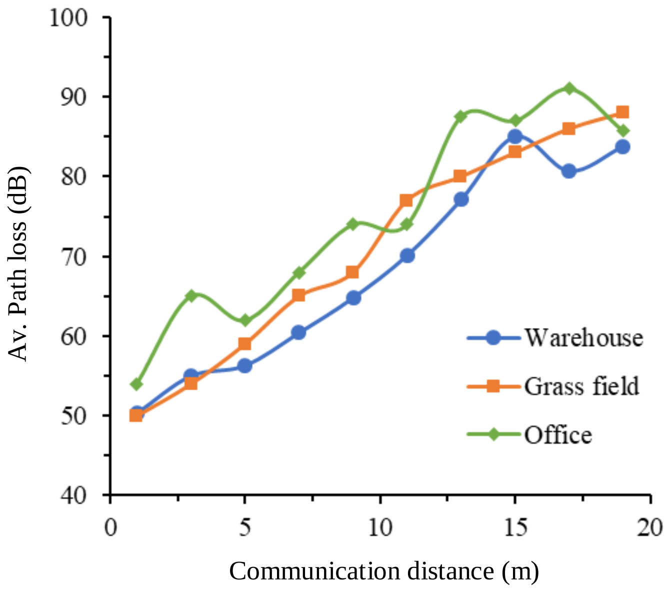


***Figure 17**. Relationship between communication distance and average path loss for different WSN environments.*

These observations confirm findings from previous works, such as the quality of wireless communication links between low-power sensor devices is significantly influenced by the environment. The analysis has also gone further and quantified the magnitude of the spatial effects and observed the characteristics of path loss in multiple WSN environments, when different TP levels are considered and state-of-the-art radio hardware is implemented. Observations presented in this section highlight that wireless link quality in WSN environments exhibits characteristics which cannot be captured by simplistic theoretical models. Further highlighting that link quality needs to be estimated online, in real-time, using metrics generated internally to the network.

4.4 Temporal Characteristics

The dynamic nature of the transmission medium was characterised through empirical profiling the temporal variations. Basic observations of the chosen test environments highlight that multiple potential sources of temporal variation exist. As documented in *2.2.9.2 Temporal Characteristics*, these variations can be categorised into three patterns:

1. **Small fluctuations**. Small fluctuations are the result of multipath fading, and changes in temperature and humidity.
2. **Large fluctuations and disturbances**. Large fluctuation and disturbance patterns are typically caused by shadowing and fading effects of humans, moving doors and other objects.
3. **Continuous large fluctuations**. Continuous large fluctuations are predominantly the result of interference from high-bandwidth, high TP, co-habiting networks (e.g. adjoining Wi-Fi networks) and appliances operating in the same frequency band (e.g. microwave ovens).

The likelihood that a temporal pattern will exist in a specific communication link will be dependent on the environment. For example, an office environment is more likely to be affected by continuous large fluctuations from adjoining Wi-Fi networks, whilst a grass field environment is more likely to suffer from small fluctuations because of temperature and humidity changes. Through analysing the link quality over a range of time periods and test conditions, all three of these temporal patterns were observed over the three test environments.

4.4.1 Small Fluctuations

To monitor small fluctuation temporal patterns, a three-day experiment in a grass field environment was conducted. This environment was chosen because it was remote and away from other wireless networks and human activity. On top of this, it was likely to be subjected to temperature and humidity changes. In Figure 18 the average path loss over time is plotted for a one-hour period where the greatest variance in link quality was observed. The 97% confidence intervals are plotted to show the variance in the measured parameter over the measurement window.

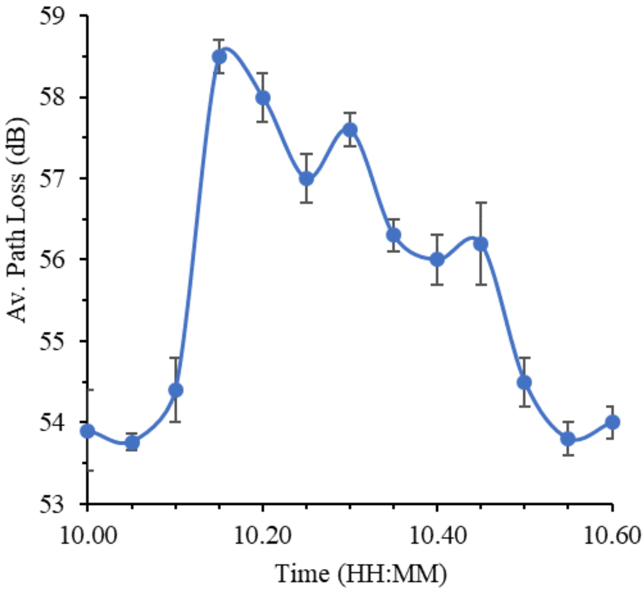


***Figure 18**. Average path loss over time in a grass field environment.*

The results from the grass field environment show that the path loss changes slowly but noticeably over time. As seen in Figure 18, the maximum change in path loss over a five-minute window is 4 dB. Comparing this temporal fluctuation to visual observations of the test environment, it was found that the test site received heavy rain between 10.15-10.25. During this time and for a period afterwards, the path loss was higher. This is thought to be attributed to two phenomena. The first is rain fade, i.e. increased atmospheric absorption because of increase water vapour. The second, and more likely cause of this temporal variation, is an increased reflective path signal strength resulting to increased destructive interference at the receiver.

By means of further investigation, the two-ray path model is applied to see if the reflected signal path will lead to constructive or destructive interference at the receiver. As seen in Figure 19, the two-ray path loss model shows that the signal at the receiver is a combination of the line-of-sight (LOS) and non-line-of-sight (NLOS) ground reflected path. At the receiver they will lead to either constructive or destructive interference depending on the communication distance (d), wavelength (λ) and antenna elevations of the transmitter and receiver (h_t and h_r, respectively) as described by Equation 27. Applying Equation 27 to the application (d = 5 m, f = 868 MHz, h_t and h_r = 0.5 m), the reflective path will be 51.9^0 out of phase which would result in destructive interference at the receiver.

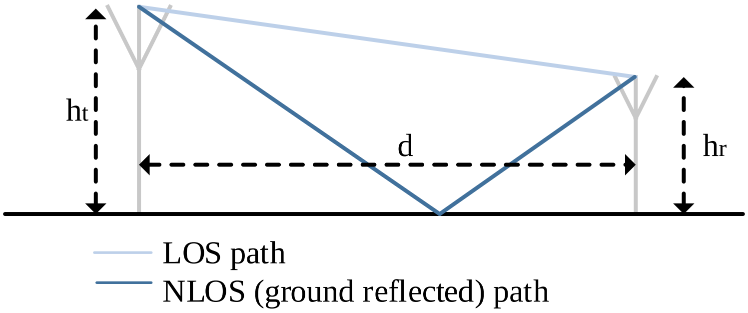


***Figure 19**. Two-ray path model.*

$$\theta = \frac{2\pi}{\lambda}\left(\sqrt{d^2 + (h_t - h_r)^2} - \sqrt{d^2 + (h_t - h_r)^2}\right)$$

***Equation 27**. Two-ray path model.*

The power of the reflected path is dependent on the ground reflection coefficient and is a factor of the permittivity and conductivity of the ground. During the rain shower, the ground becomes wet which increases the ground conductivity and subsequently increases the power of the reflective path. This in turn leads to increased destructive interference at the receiver because the reflective path is out of phase. As seen in Figure 18, the path loss is still higher after the rain shower finishes so this temporal effect is more than likely the result of increased reflective path signal strength rather than rain fade.

4.2.2 Large Fluctuations and Disturbances

To observe large fluctuation temporal patterns caused by shadowing effects of humans and other moving objects, a one-hour experiment was conducted in a warehouse environment. The nodes were configured to transmit beacon frames at shorter time periods than in *4.4.1 Small Fluctuations* to capture the temporal factors which may occur over very short time periods (e.g. moving machinery in the network area). The results for a fifteen-minute window which showed the highest levels of temporal variation are presented in Figure 20.

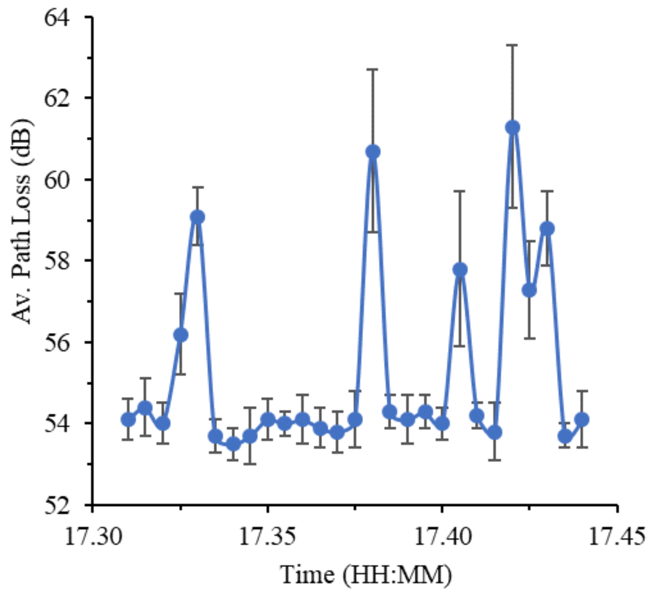


***Figure 20**. Average path loss over time in warehouse environment.*

As seen in Figure 20, the average path loss changed by up to 7 dB over small time periods. Correlating the data with visual observations of the test environment, these large changes in path loss were seen to be caused by human presence and moving machinery obstructing the LOS communication path. The confidence intervals shown in Figure 20 are much larger than those observed during the study on small fluctuation temporal patterns (Figure 18). To explain the cause of this, the raw data captured for the time period with the greatest variance (17:41) is shown in Figure 21.

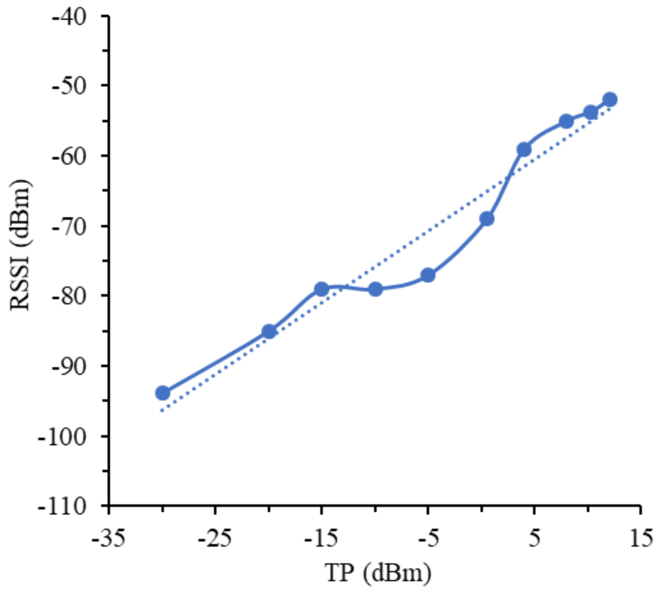


***Figure 21**. Relationship between RSSI and TP in warehouse environment.*

From Figure 21, it can be seen that the relationship between RSSI and TP exhibits characteristics which are contrary to theory (Equation 6) and dissimilar to the typical performance shown in Figure 16. This is believed to be caused by temporal factors changing over the measurement window. For example, the measurement window is typically around six seconds, which is larger than the time period of some of the temporal fluctuations (e.g. human walking across the direct LOS communication path).

4.4.3 Large Continuous Fluctuations

To observe large continuous fluctuation temporal patterns, packets were sent in quick succession in an office environment. The sink was intentionally placed 3m from a smart energy node to see the effect that interference has on path loss. The distribution of RSSI samples over a one-minute sampling window are presented in Figure 22.

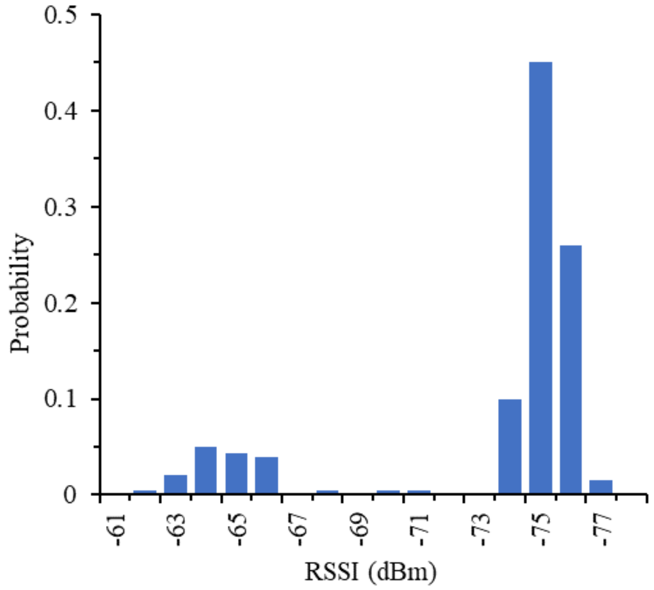


Figure 22. *Distribution of path loss samples in office environment.*

Figure 22 shows two distinct groups of RSSI samples, around -64 dBm and -75 dBm. Comparing the RSSI samples against the activity indicator on the front panel of the smart energy meter, the RSSI samples around -64 dBm are representative of the link conditions when the interferer is active. This is believed to be a result of RSSI following an additive model whereby it represents the sum of all signals in the band of interest (i.e. representative of signal, noise and interference powers) as described algebraically in Equation 12. Further analysis of the results highlighted that fewer packets were successfully received when the interferer was active, despite the RSSI being higher. It is often assumed that a higher RSSI value represents lower probability of a bit error at the receiver but this study highlights that the relationship between RSSI and communication reliability is not fixed and is affected by interference.

Clearly, the magnitude of large continuous temporal patterns are dependent on a number of application specific factors of the interferer and the network, such as; TP, communication distance, carrier frequency, modulation technique and channel access mechanism. However, results presented in this section highlight that large continuous fluctuation patterns exist in typical WSN environments and they can significantly affect the relationship between TP and RSSI.

4.5 Summary

Through considered test methodologies and a rigorous statistical analysis of the link quality, the spatial and temporal characteristics of the transmission medium in typical WSN environments have been identified and quantified. The results highlight that link quality in WSNs exhibits complex and dynamic tendencies which are contrary to simplistic deterministic models. These results further highlight that link quality needs to be estimated online, in real-time, using resources internal to the network. On top of this, meta-data has been collected which is representative of link quality in real-world WSN applications. This will be used to optimise and test the performance of the proposed TPC protocol.

Chapter Five: Assessment of Link Quality Metrics

5.1 Introduction

In order to identify and maintain the optimum transmission power (TP), the wireless link quality needs to be continually evaluated in real-time, using resources internal to the network. As documented in *2.3.2 Link Quality Properties*; channel quality, packet delivery and channel stability properties need to be captured to ensure optimum performance from both energy efficiency and communication reliability perspectives. The high-level overview of current link quality estimators (LQEs) presented in *2.3.4 Comparison of Link Quality Estimators* highlighted that no current solutions monitor the link quality properties required for a transmission power control (TPC) protocol. Subsequently, there is a requirement for a new LQE to be developed which is tailored to the monitoring requirements of a TPC protocol and practical to implement on the resource constrained hardware.

The most suitable link quality metrics used to compute the various link quality properties are currently unclear and previous works have presented conflicting views of the matter. For example, in [30] [35] it is argued that receive signal strength indicator (RSSI) is the best metric to quantify channel quality properties, whilst in [10] [36] this is disputed and link quality indicator (LQI) is recommended. In this chapter the sampling requirements of a TPC protocol are compared against the characteristics of WSNs to evaluate the performance of various link quality metrics. From this, recommendations on the most suitable metrics to use for a TPC protocol with energy efficiency objectives are made.

Aside from performance in respect to the measurement of the specific link quality property, the high-level characteristics which are most desirable for link quality metrics are as follows:

- **Practical to implement.** As described in *2.0 Introduction to Wireless Sensor Networks*, WSNs are constrained in energy, processing and memory domains. To ensure that the protocol is practical to implement on the resource constrained hardware typically used in WSNs, the metric should require few samples and minimal computation.
- **Minimal sampling time window.** As identified in *4.4 Temporal Characteristics*, wireless link quality in WSN environments can be highly dynamic and channel throughput can be very low. This results in the number of samples over which the link conditions remain stable and for which the link quality properties can be quantified being very low.
- **Universally available.** WSNs use chipsets which are compliant to several different standards and manufactured from several different vendors. To ensure that the protocol can be applied to a wide range of WSN applications, the link quality metrics should be standard and hardware agnostic.

5.2 Channel Quality

Channel quality represents properties of the received signal (e.g. power of the received signal, modulation quality of the received signal or the ratio of the signal to noise power). Channel quality properties need to be captured for the following two reasons:

1. To provide a quantitative assessment between the configurable parameter, in this instance TP, and the resulting received signal. This relationship needs to be established for a dynamic TPC algorithm to be applied which, as described in *2.1.5 Transmission Power* Control Algorithms, outperforms linear and binary based solutions.
2. To allow a link quality threshold (LQT) to be generated. Many current TPC protocols ([10] [35] [80]) tune the TP to a target value of the channel quality property, commonly referred to as the LQT. Operating at the LQT is predicted to yield the highest energy efficiency, i.e. high probability of successful packet transmission with little excess power at the receiver.

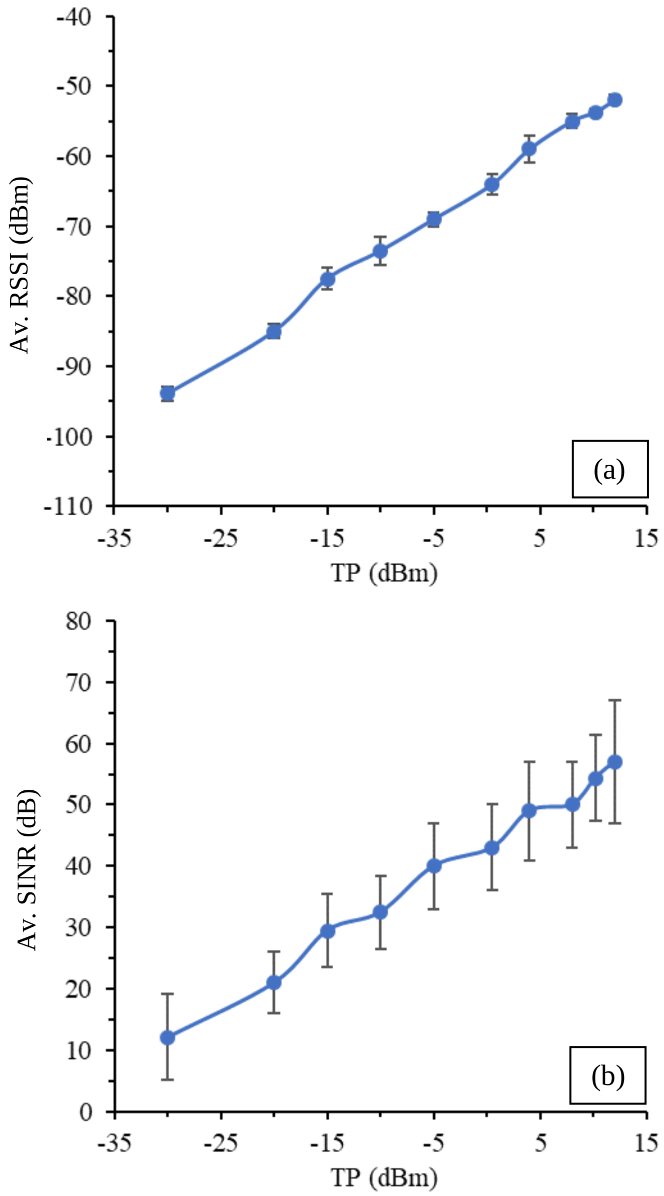
The rest of this subsection compares the performance of channel quality link metrics in respect to these two measurement criteria.

5.2.1 Quantitative Assessment between Transmission Power and the Received Signal

Previous TPC protocols have used an array of link quality metrics to provide a quantitative assessment between TP and the received signal, including; RSSI in [30] [35], LQI in [10] [36] and signal-to-noise-ratio (SNR) in [17]. As seen in Table 3, Signal-to-interference-and-noise ratio (SINR) can also be used and although not implemented in any published works on TPC, several have considered its use. To compare the performance of these different metrics, their relationship with TP has been analysed. SNR was excluded from the analysis because its computation requires features which are not common for all WSN hardware (namely clear channel assessment modes [17]) so it fails to meet the criteria of universally available.

To compare the link quality metrics against TP, an experimental WSN was created. The WSN setup is similar to that used in

Chapter Four: Empirical Study of Link Quality Assessment in Wireless Sensor Networks, with the basic operation explained in Figure 14. The experimental WSN was installed in a grass field environment and the three link quality metrics were captured, averaged and compared against TP over a communication distance of 10 m. The results are presented in Figure 23. The 97% confidence intervals have also been plotted to show the variance in the parameter over the measurement window.



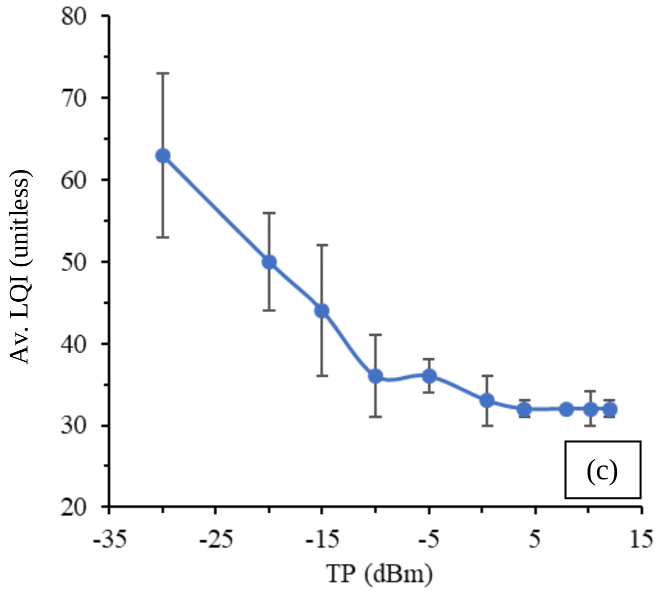


Figure 23. *TP against average RSSI (a), SINR (b) and LQI (c).*

The results in Figure 23 show that RSSI, SINR and LQI metrics have a detectable correlation to TP, over a certain range and over a short time period. This is in line with the observations presented in other empirical studies The relationship between LQI and TP, as seen in Figure 23c, shows approximately linear correlation for part of the TP range (from -30 to -10 dBm). This metric can however be seen to saturate at a value of 32 (unitless) which is the maximum quality frame detectable by the radio hardware [63]. The results highlight that the LQI metric suffers from high variance (up to 32 % of the measurable range) which means that multiple samples and a post processing technique would need to be applied. As LQI samples are dependent on over-the-air packet transmissions, the time period to obtain multiple samples can be quite large and this in turn could reduce the agility of the TPC protocol. The dependency of over-the-air packet transmissions also results in a large energy overhead.

RSSI and SINR metrics show strong linear correlation against TP over the full TP range as seen in Figure 23a and Figure 23b, respectively. RSSI readings can be seen to be more stable than SINR readings, with the observed variance being less than 2 dB (5% of the measurable range). SINR readings have much higher variance at between 5 and 10 dB (up to 25% of the measurable range) even though they are measured from the same register. The SINR metric has been decomposed into receive power (P_r) and noise plus interference power ($P_n + P_i$) elements to identify the source of the variance. The distribution of SINR samples and its two elements (P_r and $P_n + P_i$) are shown in Figure 24 for the sampling window which showed the highest variance (TP = -30 dBm).

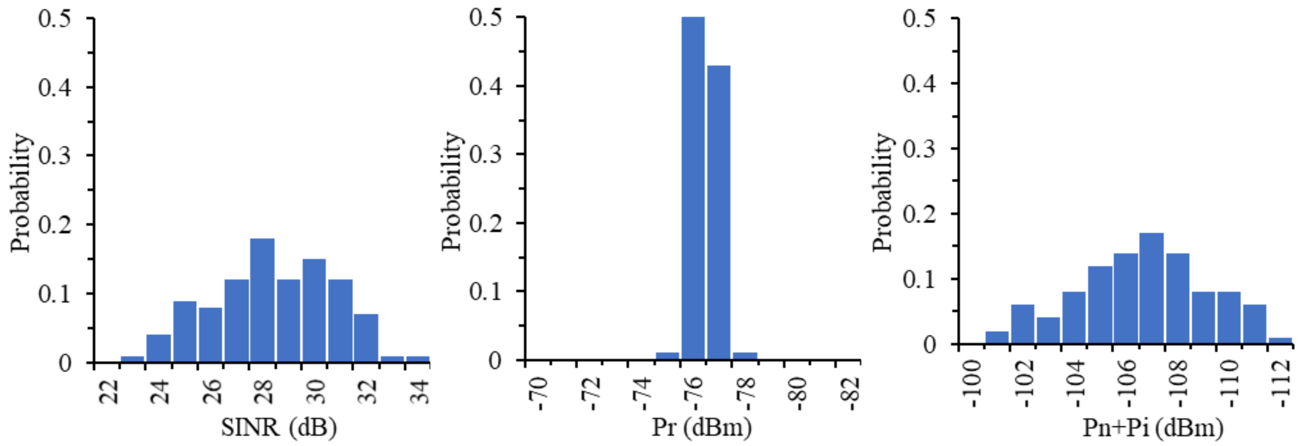


***Figure 24**. SINR (left), P_r (centre) and P_n+P_i (right) distributions.*

From Figure 24 the variance in the SINR metric can be seen to be the result of the $P_n + P_i$ element rather than P_r. To better characterise this, $P_n + P_i$ samples at different power levels have been measured, with the results presented in Figure 25. Different levels of $P_n + P_i$ were introduced at the receiving node through incorporating an interfering node into the network. The interfering node was composed of the same hardware as was used in the experimental network (Anaren A1101R08A radio) and was configured to operate in a transmit test mode [63]. This mode of operation makes it possible to generate a continuous burst of interfering packets with a modulated carrier. The interfering node was operated at several different TP levels (denoted as Int TP in Figure 25) to introduce various interference powers at the receiver.

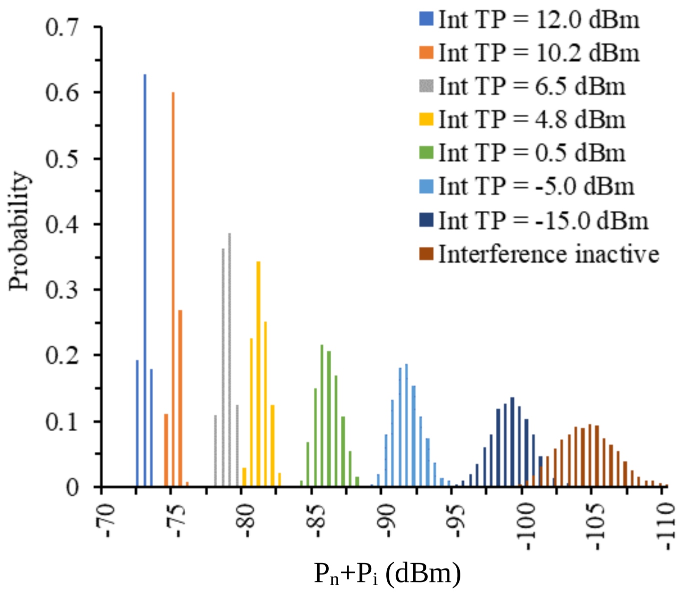


***Figure 25**. Distribution of P_n+P_i samples at different power levels.*

The variance in $P_n + P_i$ at different power levels is summarised in Figure 26.

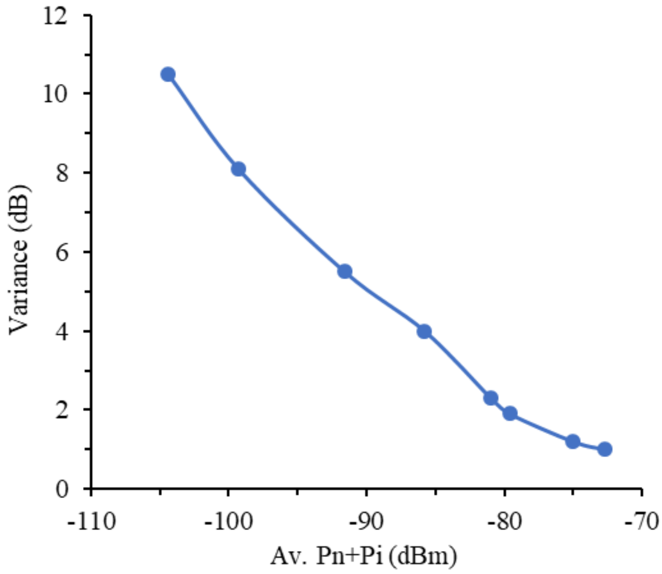


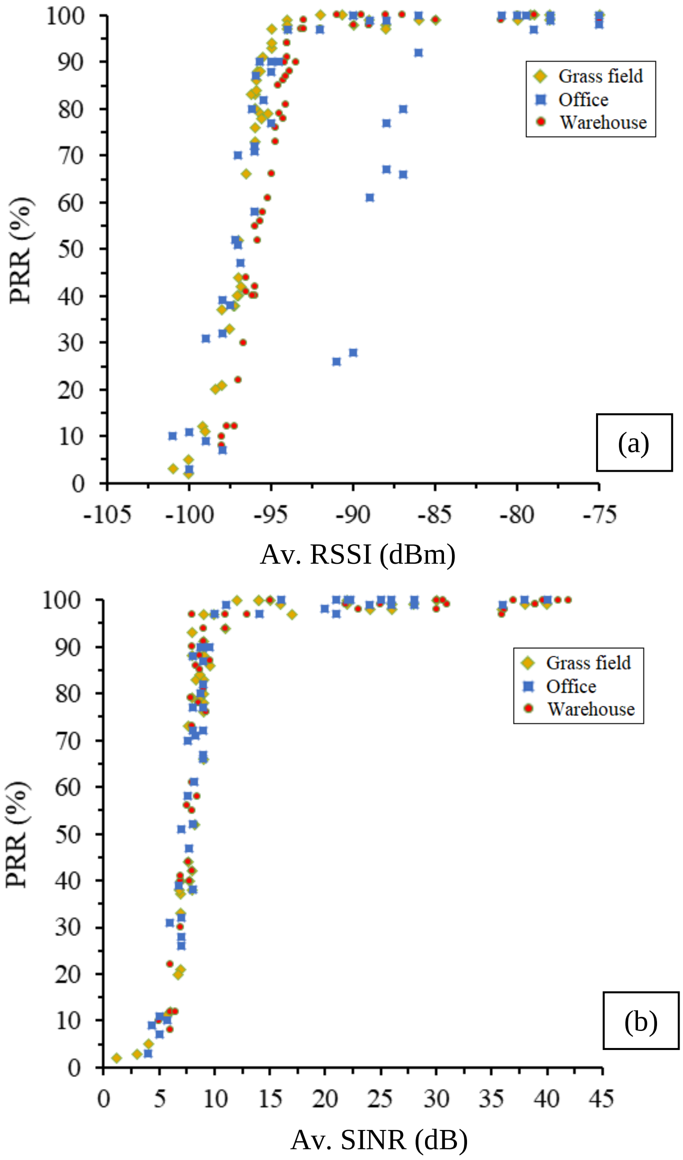
Figure 26. *Variance in Av. (P_n+P_i) at different power levels.*

The results in Figure 25 show that the variance in $P_n + P_i$ metric follows a Gaussian distribution and Figure 26 shows the magnitude of the variance is dependent on the power level. The authors believe the variance is the result of thermal and electronic sources having a significant influence on $P_n + P_i$ measurements when it is low in magnitude. When $P_n + P_i$ is much greater in magnitude, which is often the result of interference from wireless sources either internal or external to the network, the effects of thermal and electronic sources are not as pronounced and the variance in the metric is minimal. These results highlight that multiple samples and a post processing technique is required when using the SINR metric. The energy, memory and computational resource requirements to address the variance in SINR are significantly lower than LQI since fewer samples are required and SINR samples are independent of over-the-air packet transmissions.

5.2.2 LQT Generation

The LQT represents the lowest possible value of the channel quality property which can be used before packet losses occur due to insufficient link budget. A desirable characteristic of the LQT is to be directly mapped to the packet delivery properties of the communication link. To compare the performance of different link quality metrics, their correlation to packet reception ratio (PRR) was analysed over three test environments which are typical of WSN applications; a grass field, a warehouse and an office (as seen in Figure 15). The experimental setup is the same as that described in

Chapter Four: Empirical Study of Link Quality Assessment in Wireless Sensor Networks, with the basic operation explained in Figure 14. For each transaction, the three channel quality metrics (RSSI, LQI, SINR) were captured along with the sequence number to quantify the PRR. PRR was calculated over a sampling window size of 100 packets. Over the sampling window every effort was made to ensure the link conditions remained constant. The communication distance was varied between sampling windows to characterise the link quality metrics over their full range. In Figure 27, the average value of the link quality metric measured over the complete sampling window is plotted against the PRR for the three test environments.



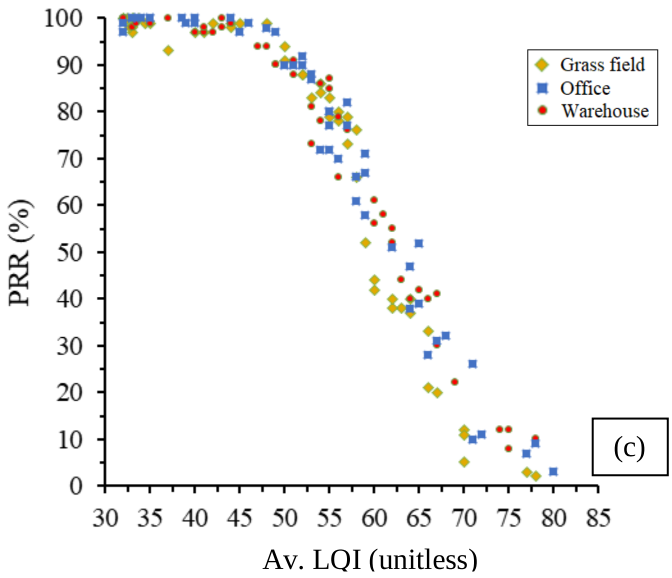


Figure 27. *PRR against average RSSI (a), SINR (b) and LQI (c) in grass field, office and warehouse environments.*

Analysis of the results show that the LQT is fairly consistent for SINR and LQI metrics, across all three environments, at between 10-11 dB and 46-48 (unitless), respectively. Although not shown in Figure 27, it was previously identified that both SINR and LQI metrics suffer from a high level of variance over the measurement window so multiple samples and a post processing technique would be required to identify the LQT.

The LQT for RSSI in the grass field and warehouse environments were similar at -94 and -93 dBm, respectively. However, the relationship between RSSI and PRR in an office environment showed several spurious data points (as seen by the blue square data points in Figure 27a) resulting in a LQT of -85 dBm. Visual observations of the office environment identified a smart energy wireless network in close proximity to the receiving node. To determine whether it is interference that results in the relationship between RSSI and PRR being environmentally dependent, this relationship has been analysed with a controllable source of interference (an additional node operating in a transmit test mode) in the network. The results are presented in Figure 28.

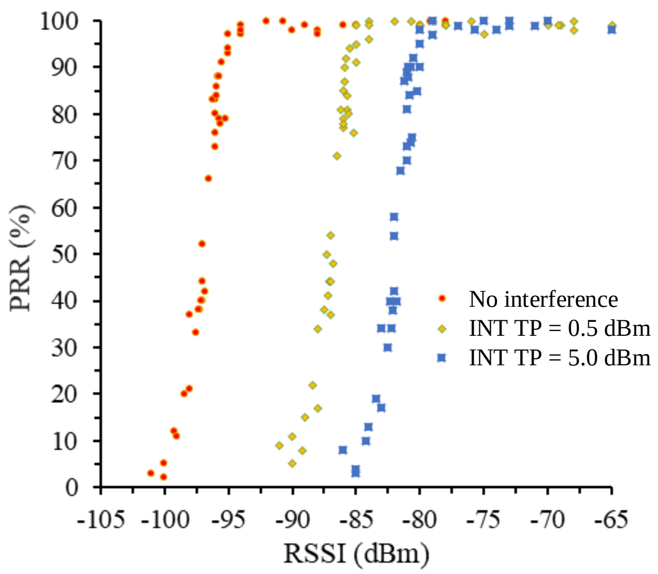


Figure 28. *PRR against RSSI with a controllable source of interference in the network.*

The results presented in Figure 28, clearly show that the relationship between PRR and RSSI is severely affected by interference. The author believes this is a result of RSSI following an additive model whereby it represents the sum of all signals in the band of interest (i.e. representative of signal, noise and interference powers) as shown algebraically in Equation 12. Thus, interference may increase the RSSI and degrade the packet delivery properties of the communication link. This highlights that the relationship between RSSI and PRR will be environmentally dependent and liable to change over time depending on the presence and severity of interference. This is a very undesirable characteristic for a link quality metric from which a LQT is to be generated and previous works ([10] [80]) which implement this would suffer from poor energy efficiency and unreliable operation due to gross errors in the link quality estimation process.

The relationship between link quality and PRR was also analysed for LQI and SINR metrics with interference present in the network. The results showed negligible changes to the LQT. This is a result of SINR and the Texas Instrument implementation of LQI (which is based on SNR estimation [63]) having a fixed relationship to the PRR as described by Equation 11. Other implementations of the LQI metric may not exhibit the same characteristics since they may be estimated using different methods. The relationship between PRR and SNR/SINR is dependent on the physical layer particulars of the radio (e.g. data rate, modulation type, packet length) so will vary for different radio hardware and application configurations. The physical layer configuration of the radio is however typically fixed over the lifetime of the network so the LQT wouldn't need to be continually updated.

Although not observed in the above empirical study, previous works ([21] [61]) have highlighted that multipath wave propagation and fading can affect the relationship between channel quality and packet delivery metrics. As described by the two-ray path model shown in Figure 19, when two or more signals are combined at the receiver, the resulting signal amplitude can be increased or decreased as a result of constructive or destructive interference at the receiver, respectively. If multipath effects only result in signal magnitude changes (no/ negligible effect on phase and bit spread), the relationship between channel quality and packet delivery metrics should remain constant.

However, multipath can lead to time dispersion of the original signal resulting in inter symbol interference (ISI), as well as, phase shifts causing distortion. These phenomena can affect the relationship between channel quality and packet delivery metrics as shown in Figure 6. In real-world wireless links, the effect of multipath is often more complex than that described in the two-ray model because the receiver might see a combination of several different signals with each traversing a different path and when scattering exists in the channel, a wave will experience a phase shift, polarisation changes or some other change when it encounters a scattering surface.

The reason for the empirical results presented in this chapter showing clear LQT values and multipath factors not being observed is not clear. Previous works ([61]) have noted that wireless networks which use phase shifting modulation techniques and/ or high data rates are often more sensitive to ISI and distortion. The experimental network used in this chapter uses a low data rate (1 kbps) and a frequency shift keying modulation technique, and the author believes these could be two contributing factors towards the minimal severity of multipath effects. Nevertheless, some WSNs do use high data rates and phase shift keying modulation techniques so for the proposed TPC protocol to work efficiently in these networks, the effects of multipath should be considered and mitigated.

5.2.3 Summary

The observations presented above have been summarised in Table 5. A ranking mechanism has been used to provide a quantitative assessment between the different metrics. Four evaluation criteria have been identified and each of these have a relative weight associated with it. In the table below, each of the metrics are scored against the evaluation criteria and the reasoning behind the scorings are presented. Note the relative weightings and scores provided in Table 5 and Table 6 (page 81) are subjective and are based on the experience of the author.

Channel quality metric	Range (25%)	Variance (15%)	Detectable correlation to transmission power (30%)	Detectable correlation to PRR (30%)	Score (%)
RSSI	**22** RSSI has a high range which is unlikely to saturate so will allow the TP to be compared against the received signal over the complete TP range.	**13** RSSI has low variance (5% of measured range over short time periods) so a single sample is sufficient to capture the channel quality.	**27** RSSI has a direct linear correlation to TP over short time periods.	**7** The correlation between RSSI and PRR is environmentally dependent since RSSI represents the sum of all input powers and thus, is affected by varying levels of interference and noise power.	**69**
LQI	**10** LQI has a low range which is likely to saturate and thus, will not allow the TP to be compared to the received signal for the complete TP range.	**3** LQI has high variance (35% of the measured range over short time periods) so multiple samples and a post processing technique is required. The number of samples and the dependency of over-air packet transmissions results in large sampling windows and high energy overhead.	**2** LQI doesn't represent a single property of the received signal as it is calculated using receiver energy detection, SNR estimation or a combination of these metrics. Since LQI is not based on a single property of the received signal, it cannot be accurately mapped to a physical phenomenon, such as TP.	**10** The correlation between LQI and PRR is dependent upon how LQI is calculated. Implementations of LQI that use SNR estimation have strong correlation to PRR and the relationship is not affected by environmental factors. The relationship between LQI (when calculated based on SNR estimation) and PRR is however dependent on a number of physical layers particulars of the radio so will vary for different radio hardware and application configurations.	**25**
SINR	**22** SINR has a high range which is unlikely to saturate so will allow the TP to be compared against the received signal over the complete TP range.	**9** SINR has high variance (5-25% of the measured range over short time periods) so multiple samples and a post processing technique is required. Samples are independent of over-air packet transmissions so the variance can be addressed with minimal energy overhead and over short sampling windows.	**27** SINR has a direct linear correlation to TP over short time periods.	**25** The correlation between SINR and PRR is not affected by environmental factors. It is however dependent on a number of physical layers particulars of the radio so will vary for different radio hardware and application configurations.	**83**

Table 5. *Comparison of link quality metrics for evaluating channel quality properties.*

From Table 5 it can be seen that LQI scores the lowest. This is because it does not have a detectable correlation to TP, it doesn't represent a fixed property of the communication link (since it could either be based on SNR, modulation quality or a combination of the two) and it has high variance. RSSI is seen to outperform LQI and it is the best metric to use for providing a quantifiable assessment of TP over a single sample. However, confirming observations from previous works, RSSI does not have a fixed relationship to PRR when interference exists in the network since it represents the sum of the signal, noise and interference powers.

When considering all the requirements of a link quality metric for measuring the channel quality properties of a communication link, SINR can be seen to be the most suitable. It has a linear correlation to TP, has sufficient range so can be compared against the configurable parameter over the full TP range and it has a detectable correlation to PRR which is not influenced by the environment. SINR does suffer from variance which the authors believe to be a result of thermal and electronic sources, especially when the noise and interference power is weak. The energy overhead to address the variance in the SINR metric is however minimal because multiple noise and interference power samples can be taken independently of over-the-air packet transmissions. The number of samples required and the complexity of the post processing technique is also minimal so the memory and processing overheads are low, which makes it practical to implement on the resource constrained hardware.

5.3 Packet Delivery

As discussed in *2.3.2 Link Quality Properties*, packet delivery properties of the communication link need to be monitored for the following three reasons:

- To mitigate against the exposed and hidden node problems which are exacerbated by the implementation of a TPC protocol.
- To identify when the communication reliability has been detrimentally affected by the operation of the TPC protocol as a result of insufficient link budget.
- To identify when multiple packet retransmissions occur as these significantly affect the energy consumed per transaction.

As shown in Figure 9, packet delivery properties can be captured by either a PRR or required number of packet retransmission (RNP) based software link quality estimator (LQE). Several variations of these estimators exist (e.g. KLE [66], ETX [68] and Four-bit [69]), however, their high-level characteristics are fairly similar so they have not been considered in this analysis. In Table 6 a comparison of the sampling characteristics of RNP and PRR based software LQEs is presented.

Packet delivery metric	**Sampling window (50%)**	**Memory overhead (25%)**	**Computation overhead (25%)**	**Overall score (%)**
RNP	**45** RNP is calculated over a single transaction so the sampling time window is limited to the maximum number of packet transmissions allowed by the protocol (typically no more than 5).	**22** As RNP is calculated over a single transaction, very few samples need to be cached to compute this metric.	**22** The computation of RNP is very simplistic and is practical to implement on processors with minimal processing capabilities.	**87**
PRR	**20** PRR is calculated over a number of transactions. As was observed in [64], the number of transactions required to accurately predict the PRR is dependent on the connectivity region the link exists in. For links in the connected or disconnected regions, PRR can be estimated over a small number of packets, however links in the transitional regions typically require significantly more samples (e.g. over 20). With the dynamic characteristics of wireless links in WSNs and the typically low throughput, link quality metrics which require multiple samples over which the link conditions remain consistent are generally impossible to implement.	**10** As PRR can require a large number of samples, the memory overhead can be significantly large and impractical to implement on WSN hardware.	**20** Although PRR is computed from multiple samples, the computation is fairly simplistic and is practical to implement on resource constrained hardware with minimal processing capabilities.	**50**

***Table 6**. Comparison of link quality metrics for evaluating packet delivery properties.*

Comparing the characteristics of PRR and RNP based estimators with the requirements of a TPC protocol for WSN applications, RNP based estimators can be seen to be superior. This is because they can be computed over a single transaction, feature few samples and require very little processing in their computation. On top of this, only RNP based estimators can assess the number of packet retransmissions which occur over the transaction. Since packet retransmissions consume considerable energy resources (as seen in *Chapter Three: Radio Energy Considerations*) identifying when they occur and mitigating against them is a key requirement to ensure energy efficient operation.

5.4 Channel Stability

Channel stability represents the variability level of the communication link. Channel stability is typically measured through analysing the variance in the packet delivery or channel quality properties of the communication link. Through reusing the same metrics used to compute other link quality properties, the sampling and memory overhead required to capture the channel stability properties is minimal. Since the metrics used to compute the channel quality properties typically have a larger dynamic range and they are more agile so can react quickly to link quality changes, their use is recommended.

5.5 Summary

In this chapter the suitability of various link quality metrics for evaluating the three critical link quality properties for a TPC protocol have been analysed. This study highlighted that using SINR to capture the channel quality properties of the communication link is most suitable since; it has a detectable correlation to TP, has a large measurement range so can be compared against the configurable parameter over the full TP range and has a detectable correlation to PRR even when interference exists in the network. Although SINR does suffer from a considerable level of variance over the measurement window, especially when the interference and noise power is weak, the variance can be addressed using low computation, memory and energy overhead methods which are practical to implement on the resource constrained hardware.

A simple high-level comparison of link quality metrics for capturing packet delivery properties of the communication link highlighted that RNP based metrics outperformed PRR based counterparts. This is because they require less computation, fewer samples and can be calculated over smaller sampling windows. On top of this, only RNP based LQEs can assess the number of packet retransmissions.

An assessment of link quality metrics for capturing channel stability properties found that reusing channel quality metrics was the most practical since they have the greatest dynamic range and they are the most agile. On top of this, reusing channel quality metrics would minimise the sampling overhead so there use in recommended for capturing channel stability properties.

Chapter Six: Novel Holistic Transmission Protocol Control Proposal

6.1 Introduction

Following on from the link quality metric recommendations made in *Chapter Five: Assessment of Link Quality Metrics*, a new transmission power control (TPC) protocol, named holistic TPC (HTPC) is proposed. In line with the recommendations made in *2.1.4 Transmission Power* Control *Protocols* and *2.1.5 Transmission Power* Control Algorithms, HTPC implements a dynamic algorithm and modulates the transmission power (TP) on a per-packet basis. The optimal TP is estimated through capturing channel quality and packet delivery properties to provide a real-time estimation of the minimum channel gain, and capturing channel stability properties to implement an adaptive fade margin to address channel estimation errors between measurement and operational windows.

6.2 Channel Gain

The minimum channel gain ($CG_{\min}$) is an estimate of the minimum amount of gain required at the transmitter to ensure the intended receiver can detect the transmitted signal. $CG_{\min}$ accounts for the factors which affect the relationship between transmitted and received signal powers. As detailed in *2.2.3 Relationship between Transmission and Reception Powers*, this includes; path loss, noise and interference. In reference to the system model (Figure 1), $CG_{\min}$ can be estimated from the noise and interference power ($P_n + P_i$), TP (P_t) and received power (P_r), as follows:

$$CG_{\min} = P_t + (P_n + P_i) - P_r$$

Equation 28*. Minimum channel gain for a single packet.*

The simplistic expression shown in Equation 28 needs to be expanded to account for the following:

- **Variance in noise and interference power samples.** As observed in *5.2 Channel Quality*, $P_n + P_i$ samples suffer from high variance, particularly when it is low in magnitude. As such, multiple samples and a post processing technique needs to be applied.
- **Received power samples only being available for successfully received packets.** Received power measurements are taken at the receiver after a packet has been successfully received. To ensure that the channel gain is not overestimated, and that the metric represents both channel quality and packet delivery properties, the channel conditions experienced over the complete transaction (i.e. for successful and unsuccessful packet transmissions) need to be accounted for.

6.2.1 Variance in Noise and Interference Power Measurements

Using the samples collected in *5.2.1 Quantitative Assessment between Transmission Power and the Received Signal*, a simple post processing technique was developed to address the variance in the $P_n + P_i$ metric. The variance in $P_n + P_i$ is a Gaussian distribution (as seen in Figure 25) so a simplistic averaging mechanism was implemented as described in Equation 29.

$$av.(P_n + P_i) = \frac{\sum_{k=0}^{n}(P_n + P_i)_k}{n}$$

Equation 29. *Average noise and interference power.*

To determine the optimal number of samples to use in the averaging mechanism (denoted as n in Equation 29), the 99.7% confidence intervals (third standard deviation, 3σ) were calculated for different sample sizes using the worst-case scenario ($av.(P_n + P_i)$ = -110 dBm). The results are presented in Figure 29.

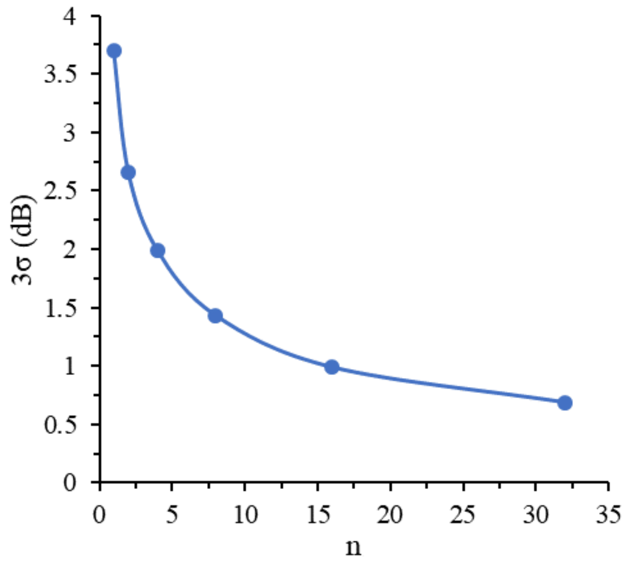


Figure 29. *Third standard deviation (3σ) of Av.(P_n+P_i) samples with different sample sizes (n).*

As expected, the more samples used to compute $av.(P_n + P_i)$, the lower the observed variance. However, caution needs to be applied since using a large sample size increases the memory, computation and energy overhead needed to capture and compute $av.(P_n + P_i)$. Second to this, $P_n + P_i$ samples are captured soon after the packet is transmitted with the assumption that this is representative of the same channel conditions experienced during the transmission. The more samples used in the post processing technique, the longer the sampling window and the lower the probability that this assumption will be representative of actual channel conditions experienced during the packet transmission. Based on the evaluation presented in Figure 29, a sample size of 10 has been selected as a suitable trade-off between metric variance and computation overhead.

6.2.2 Accounting for Unsuccessful Packet Transmissions

Acknowledgement and retransmission schemes are commonly implemented in WSNs to improve communication reliability. This means that a single transaction can consist of multiple packet transmissions if the original packet is not acknowledged. Samples of P_r are only generated for packets which are successfully received and acknowledged by the intended recipient. To ensure that the channel quality is not overestimated and is representative of the channel conditions experienced over the complete transaction, the performance of the channel when packets are not successfully received needs to be considered.

To account for this, the transmitting node assumes that the power at the receiver is equal to the noise plus interference power (i.e. $P_r = P_n + P_i$) when a packet is not acknowledged. The P_r measured over a complete transaction (P_{r_trans}) therefore becomes:

$$P_{r\_trans} = \frac{\sum_{i=0}^{RNP+1} P_{r_i}}{RNP+1}$$

Equation 30. Received power averaged over a complete transaction.

Where RNP is the number of packet retransmissions before a successful packet reception is detected.

The minimum channel gain calculated over the complete transaction ($CG_{\min\_trans}$) therefore becomes:

$$CG_{\min\_trans} = P_t + av.(P_n + P_i) - \mathrm{P}_{\mathrm{r}\_trans}$$

Equation 31. Channel gain averaged over the complete transaction.

6.3 Fade Margin

If the minimum channel gain (as described in *6.2 Channel Gain*) was used at the transmitting node, the bit error rate (BER) would be excessively high and this would have a detrimental effect on the energy efficiency as a result of packet retransmissions. The TP needs to be sufficiently higher than the minimum channel gain to ensure error free reception. This is known as the fade margin. In HTPC, the fade margin (FM) consists of fixed (FM_f) and adaptive (FM_a) elements, as seen in Equation 32.

$$FM = FM_f + FM_a$$

Equation 32. Fade margin.

6.3.1 Fixed Fade Margin

FM_f represents the minimum fade margin required to ensure sufficient SINR at the receiver for error free reception. It is very similar in nature to the link quality threshold (LQT) used in previous works ([10] [35] [80]) and analysed empirically in *5.2.2 LQT Generation*. The fixed element is based on the radio configuration, e.g. modulation type, packet size, frame level encoding and data rate. As the radio configuration is typically fixed throughout the operation of the network, a fixed fade margin to account for these factors is a reasonable approach.

The fixed fade margin can be calculated through one of the following approaches:

- **Offline**. If the radio configuration is known, the minimum fade margin can be estimated offline and programmatically implemented prior to network installation. The relationship between SINR and PRR is well documented as described in *2.2.7 Bit Error Rate*.
- **Online**. Similar to the experiment carried out in *5.2.2 LQT Generation*, the relationship between SINR and PRR can be calculated empirically during network installation. Depending on the range and granularity of the TP levels available at the transmitting node, this relationship could be sufficiently characterised through just cycling the TP. It may however be necessary to change other link conditions, for example the communication distance, in order to fully characterise the relationship between SINR and TP.

Previous empirical investigations into the relationship between SINR and PRR carried out in *5.2.2 LQT Generation* produced similar results to the theoretical model so either approach is acceptable.

6.3.2 Adaptive Fade Margin

The adaptive fade margin is used to address channel estimation errors between measurement and operational windows which, as described in *2.3.2.3 Channel Stability*, are common in WSNs due to the dynamic network conditions and low channel throughput. The adaptive fade margin is based on the channel stability properties of the communication link and represents a trade-off between energy efficiency and packet delivery. Links with high stability result in low estimation errors so a minimal fade margin can be applied to maximise energy savings without significant risk of detrimental effects to communication reliability. Conversely, links with poor stability require a much larger fade margin to ensure sufficient communication reliability performance is achieved and to ensure packet retransmissions aren't triggered, which themselves consume significant energy resources.

To identify the optimum parameter settings to use for the adaptive fade margin, the energy efficiency (as measured by the energy consumed per bit, E_{bit}) and communication reliability (as measured by the packet reception ratio, PRR) performance properties of communication links with various fade margin parameters have been simulated. The PRR and E_{bit} performance metrics were computed offline using the generalised energy model equations (Equation 23 and Equation 24, page 55) formulated in *Chapter Three: Radio Energy Considerations* and the link conditions captured in the empirical study in

As seen in Equation 33, FM_a was derived from a multiple (i) of the standard deviation of the last n samples of the min channel gain measured over a complete transaction ($\sigma_{CG_{\min\_trans}}$) (Equation 34). The number of samples used to calculate the standard deviation (n) and the multiple of the standard deviation (i) were varied to identify the optimum parameter settings, with the results presented in Table 7 and Table 8.

$$FM_a = i \times \sigma_{\min\_trans}$$

***Equation 33**. Adaptive fade margin.*

$$\sigma_{CG_{\min\_trans}} = \sqrt{\frac{\sum CG_{\min\_trans} - \overline{CG_{\min\_trans}}^2}{n}}$$

***Equation 34**. Standard deviation of last n samples of min channel gain measured over a complete transaction.*

i	**PRR (%)**			
	***n*=5**	***n*=10**	***n*=15**	***n*=20**
0.0	84.50	84.50	84.50	84.50
0.5	90.47	99.45	99.90	99.96
1.0	94.95	99.98	99.99	99.99
1.5	97.23	99.98	99.99	99.99
2.0	98.38	99.99	99.99	99.99
2.5	99.01	99.99	99.99	99.99
3.0	99.35	99.99	99.99	99.99

***Table 7**. PRR performance with variable fade margin settings.*

i	**E_{bit} (uJ)**			
	***n*=5**	***n*=10**	***n*=15**	***n*=20**
0.0	1.54	1.54	1.54	1.54
0.5	1.40	1.14	1.11	1.10
1.0	1.30	1.12	1.28	1.37
1.5	1.27	1.38	1.68	1.83
2.0	1.28	1.69	2.10	2.31
2.5	1.33	2.03	2.54	2.78
3.0	1.42	2.40	2.98	3.26

***Table 8**. E_{bit} performance with variable fade margin settings.*

As seen in Table 7, the PRR is lower than 85% when no adaptive fade margin is applied (i = 0), further highlighting that an adaptive fade margin is required to ensure a sufficient PRR is achieved. From the heat map in Table 7, parameter settings of n > 10 or i > 1.5 are required to ensure detrimental effects to communication reliability aren't realised. Comparing these observations against the energy performance shown in Table 8, a larger than necessary value of n and/ or i results in poor energy efficiency. High values of either of these parameters results in a larger than necessary fade margin and consequently, wasted energy at the transmitter because packets could be sent at a lower TP and still be successfully received.

Comparing the results presented in Table 7 and Table 8, parameter settings of i = 0.5 and n = 10 ensure optimum performance from both energy efficiency and communication reliability perspectives. Although, similar performance could be achieved with larger n settings, this would increase the memory and computation overhead so would be less practical to implement on the resource constrained hardware.

6.4 Recommended Transmission Power

Taking into account the fade margin, the recommended TP (TP_{rec}) becomes:

$$TP_{rec} = CG_{\min\_trans} + FM_f + FM_a$$

Equation 35. *Minimum TP.*

It is often impossible to operate at the recommended TP due to the discrete power levels available in the radio hardware. The actual TP used at the transmitter (TP_{act}) and TP_{rec} are related by:

$$TP_{act} = \lceil TP_{rec} \rceil$$

Equation 36. *Recommended TP.*

A ceiling function ($\lceil \; \rceil$) is used in Equation 36, rather than the nearest available TP because as identified in *2.1.2 Transmission Power Control Modelling*, it is preferable to use a slightly higher (rather than lower) TP to minimise the detrimental effects on energy efficiency and communication reliability when a non-optimal TP is used. As an example, if TP_{rec} is -19 dBm, the next available TP level on the Texas Instrument CC1101 radio is -15 dBm [63] so the TP used for the next transaction (TP_{act}) would be set to this.

6.5 Implementation

A block diagram of HTPC is presented in Figure 30. The majority of the processing for the TPC protocol takes place at the transmitter. The transmitter is often the node in WSNs since traffic is typically upstream from node to sink (as discussed in *2.0 Introduction to Wireless Sensor Networks*). Although the node typically has lower memory, computation and energy resources than the sink, the processing has been allocated in this manner for the following reasons:

- **Scalability**. The sink is often shared amongst numerous nodes in a WSN. If the memory and processing of the TPC protocol was allocated to the sink and a large number of nodes existed in the network, there may be insufficient resources in the sink to implement the TPC protocol.

Through allocating the majority of the processing to the node, the overhead on the sink is negligible so no prior knowledge or consideration for node density and number of nodes connected to a sink needs to be carried out.

- **Metric availability**. Metrics generated remotely to the node need to be transported over wireless links. Since the chance of dropped packets over a wireless link is relatively high, it is preferable to generate metrics locally (i.e. internally to the transmitter).
- **Metric distribution**. Through localising the processing as much as possible, the number of metrics which need to be distributed in the network is minimised. This reduces the energy overhead of metric distribution.
- **Acknowledgement packet limitations**. HTPC utilises acknowledgement packets sent from the receiver to the transmitter to transport the link quality metrics generated at the receiver. Through utilising existing network traffic, there is no additional energy overhead to transport the link quality metrics. Acknowledgement packets can only carry a small amount of dynamic data (less than four bytes for Bluetooth Low Energy [14]) and need to be sent soon after the packet is received. This therefore places limitations on the number of metrics that can be transported in the acknowledgement packet and the processing time to generate the link quality metrics.

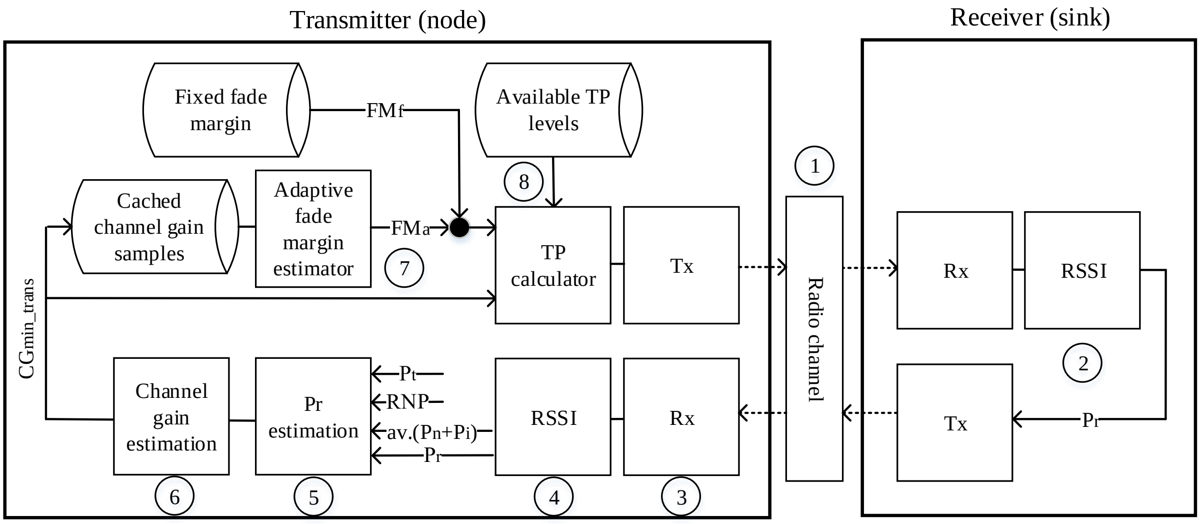


Figure 30. HTPC block diagram.

The operation of HTPC is explained below in reference to Figure 30.

1. A data packet is sent from the transmitter (node) to the receiver (sink) at a TP of P_t.
2. Upon successful reception of the packet, the receiver measures the power of the received signal (P_r) through the RSSI register. The link quality metric is subsequently sent back to the transmitter in an acknowledgement packet.
3. If the acknowledgment packet is successfully received, the P_r sample is read from the contents of the acknowledgement packet.

If no acknowledgement is received, P_r is assumed to be equal to the noise and interference power ($P_n + P_i$), and packet retransmissions are triggered.

4. $Av.(P_n + P_i)$ is measured at the transmitting node through reading the RSSI register and an averaging mechanism is applied (Equation 29).
5. The average received power over the complete transaction (P_{r_trans}) is estimated at the transmitting node (Equation 30).
6. The minimum channel gain calculated over the complete transaction ($CG_{\min\_trans}$) is estimated at the transmitting node (Equation 31).
7. The adaptive fade margin is estimated from the cached samples of $CG_{\min\_trans}$ (Equation 33).
8. The recommended and actual TPs (TP_{rec} and TP_{act}, respectively) are calculated (Equation 35 and Equation 36, respectively) and the TP register in the transmitting node is updated.

6.6 Comparison to Design Challenges

In *2.1.6 Related Works*, four design challenges were identified which needed to be addressed to increase the adoption of TPC protocols in WSN applications. The ways in which these design challenges have been addressed by HTPC are presented below:

- **Practical to implement**. HTPC requires few samples to be cached (10 bytes of data) and utilises simplistic metric evaluation techniques so is practical to implement on the resource constrained hardware. The energy overhead to implement HTPC is also negligible since it implements passive link monitoring so exploits existing network traffic to transport the link quality metrics.
- **Adaptive to link quality changes**. HTPC utilises agile link quality metrics, a dynamic tuning algorithm and updates the TP on a per-packet basis so is adaptive to the dynamic nature of the transmission medium.
- **Application, hardware and standard agnostic**. HTPC uses link quality metrics which are readily available from registers on most radio platforms used in WSNs.
- **Precise tuning algorithm**. HTPC captures more link quality properties than any other existing works on TPC. Through this, more of the energy critical properties can be accounted for and the TP can be more highly optimised to the existing and predicted future channel conditions.

6.7 Summary

In this chapter, a new TPC protocol has been proposed. HTPC captures channel quality, packet delivery and channels stability properties of the communication link to provide a real-time estimation of the link quality. The TP is modulated on a per-packet basis using a dynamic algorithm. The algorithm has been developed from first principles and has been optimised using empirical data from a range of typical WSN environments. Block diagrams and step-by-step instructions of the operation of HTPC are provided to ease implementation. A comparison of the proposed protocol to the design challenges identified in *2.1.6 Related Works* is provided to highlight how these have been addressed to help improve the adoption of TPC protocols in WSN applications.

Chapter Seven: Holistic Transmission Power Control Evaluation

7.1 Introduction

In this chapter the transmission power control (TPC) protocol proposed in *Chapter Six: Novel Holistic Transmission Protocol Control* Proposal, named holistic TPC (HTPC), is evaluated in a range of scenarios which are representative of wireless sensor network (WSN) applications. The performance of HTPC is subsequently compared against existing state-of-the-art (SoA) TPC protocols and other benchmarks through both quantitative and qualitative means.

7.2 Quantitative Evaluation

To evaluate its performance, HTPC was implemented on representative WSN hardware and incorporated into an experimental WSN. The hardware consisted of a Anaren A1101R08A radio module to implement the MAC/PHY layers which as shown in *Appendix 1: Taxonomy of state-of-the-art radio hardware commonly used in WSNs* is representative of SoA radio hardware commonly used in WSN applications. The remainder of the host protocol stack was implemented on a low-cost, 8-bit, Microchip PIC microcontroller (PIC16LF1947 [81]). The experimental WSN consisted of a number of nodes with HTPC implemented, connected to a sink in a single hop, star network topology. Only the communication link between the node and sink was optimised since (as discussed in *2.0 Introduction to Wireless Sensor Networks*) communications in WSNs are predominantly one-way (upstream) from node to sink. On top of this, the sink typically has larger energy resources so optimising this link is not as crucial.

To compare the performance of HTPC against a number of benchmarks and other protocols, the performance of the communication link at every available TP was assessed and the performance metrics were saved in local non-volatile memory. An offline computation of the stored metrics was then used to compare the performance of HTPC against the following:

- **Fixed maximum TP**. This is the maximum TP available on the radio hardware (12 dBm).
- **Optimal TP**. The optimal TP is computed as the TP which results in the lowest energy consumption. This requires the transmitter to have *a priori* knowledge of the link quality at the receiver, which the author acknowledges is infeasible to achieve in reality.
- **Adaptive Transmission Power Control (ATPC)** [10]. ATPC is one the most referenced works on TPC and it claims the highest energy savings out of all the previous works identified in *2.1.6 Related Works*. In ATPC, the TP is modulated on a per-packet basis through a dynamic algorithm that uses an autoregressive filter on RSSI samples. In [10] it is proposed that the link

quality threshold (LQT) is calculated empirically but to simplify the analysis, the LQT is assumed to be the receiver sensitivity.

- **TPC in wireless body area networks for healthcare monitoring (TPC-WBAN)** [80]. In TPC-WBAN the TP is modulated on a per-packet basis using an exponentially weighted average of the received signal strength. The tuning parameters (average weight of a sample representing an improving/ deteriorating channel and upper/ lower thresholds of channel quality) represent the balanced approach proposed in [80].

The link conditions experienced in the experimental WSN were varied to see how HTPC performs under dynamic link conditions. For this, the experimental WSN was tested across the same three environments used in

Chapter Four: Empirical Study of Link Quality Assessment in Wireless Sensor Networks so the following temporal fluctuation patterns could be applied:

- **Small fluctuations**. In the grass field environment, the experimental WSN was subjected to multipath fading and changes to temperature and humidity.
- **Large Fluctuations and disturbances**. In the warehouse environment, the WSN was subjected to shadowing effects from humans, moving machinery and other moving objects.
- **Large continuous fluctuations**. In the office environment, the WSN was subjected to interference from an adjoining smart energy wireless network.

The energy efficiency (as measured by the energy consumed per bit, E_{bit}) and packet delivery (as measured by the packet reception ratio, PRR) performance of each of the aforementioned approaches (maximum TP, optimum TP, ATPC, TPC-WBAN) were quantified using the generalised model equations (Equation 23 and Equation 24) presented in *Chapter Three: Radio Energy Considerations* and compared against the online performance of HTPC. The results are presented in Figure 31 and Figure 32. Note, since the optimum TP is a retrospective measure of the optimum channel conditions, its communication reliability performance cannot be assessed.

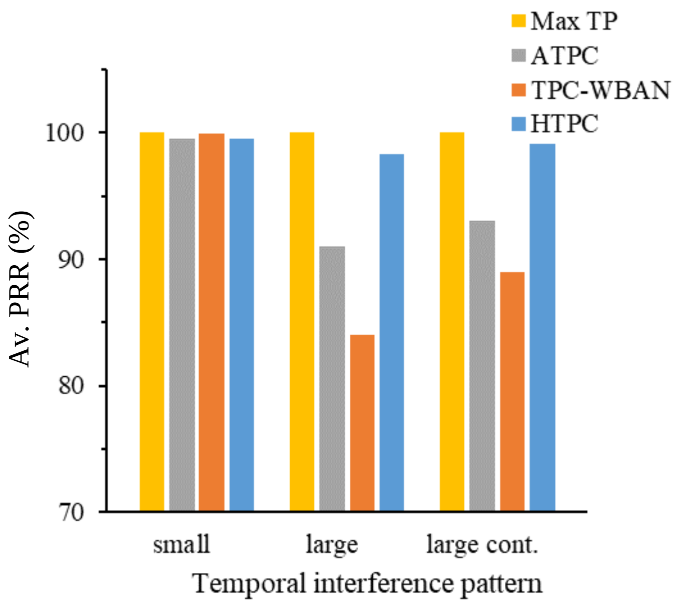


Figure 31. *PRR performance evaluation of HTPC and other approaches.*

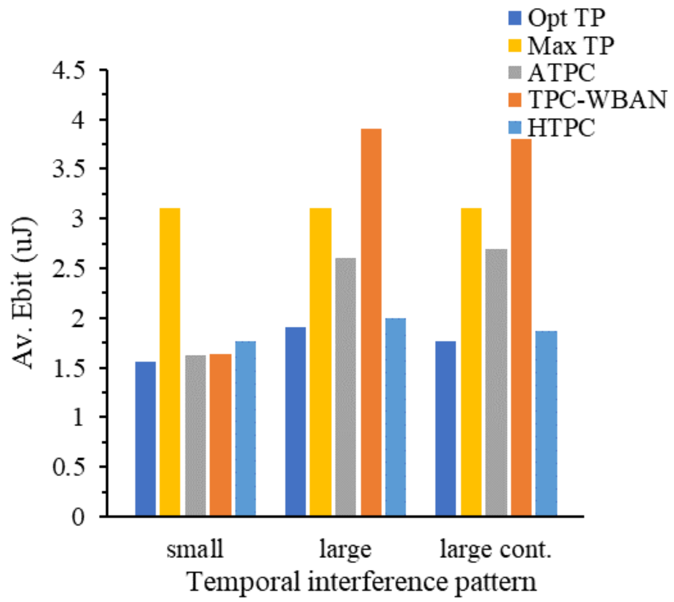


Figure 32. *E_{bit} performance evaluation of HTPC and other approaches.*

The energy performance of the various approaches have been compared against the optimal TP performance in Table 9.

<table>
<tr><th colspan="2" rowspan="2">% increase in E_{bit} compared to Opt TP</th><th colspan="4">Approach</th></tr>
<tr><th>Max TP</th><th>ATPC</th><th>TPC-WBAN</th><th>HTPC</th></tr>
<tr><th rowspan="4">Temporal interference pattern</th><th>Small</th><td>49.7</td><td>3.7</td><td>4.9</td><td>10.3</td></tr>
<tr><th>Large</th><td>38.4</td><td>26.5</td><td>51.0</td><td>4.5</td></tr>
<tr><th>Large cont.</th><td>43.2</td><td>34.8</td><td>53.7</td><td>8.8</td></tr>
<tr><th>Average</th><td>43.8</td><td>24.4</td><td>44.0</td><td>7.8</td></tr>
</table>

Table 9*. E_{bit} performance comparison between using the optimal TP and maximum TP, ATPC, TPC-WBAN and HTPC.*

Firstly, confirming observations from previous works, Table 9 shows that through using the optimum TP, rather than the current practise of using a fixed maximum TP, considerable energy savings (of up to 49.7%) can be achieved. These significant energy savings can be achieved even when the link is subjected to various temporal interference patterns and the link quality is dynamic. Although these results are application dependent since the energy savings are heavily influenced by radio hardware and environment (as discussed in *Chapter Three: Radio Energy Considerations)*, these observations further highlight that the current practise of using a fixed maximum TP yields poor energy efficiency and there are significant energy savings achievable through modulating the TP.

When the experimental WSN was tested in the relatively benign grass field environment, where only small fluctuation temporal variations exist, the energy performance of ATPC, AMC-TPC and HTPC are all relatively similar. As seen in Table 9, the energy performance of all three protocols are within 3.7 - 10.3% of the optimal TP performance. ATPC and AMC-TPC outperform HTPC marginally in this scenario. This is believed to be the result of HTPC implementing a slightly larger fade margin than the other two protocols. On top of this, HTPC was implemented on hardware and evaluated online so its performance was affected by the amount and granularity of TP levels available in the radio hardware.

The other protocols were evaluated offline where it was assumed that infinite TP levels exist. As seen in Figure 31, all three protocols delivered a PRR > 98% so their implementation did not detrimentally affect the communication reliability performance of the communication link when subjected to small temporal variations.

As seen in Figure 32, the energy efficiency performance of ATPC and AMC-TPC is poor when the network is subjected to temporal variations which are large in magnitude and occur over shorter time periods. Comparing this observation to Table 9, the energy consumption of ATPC and AMC-TPC is between 26.5 - 53.7% greater than when the optimal TP is considered. Both of these protocols detrimentally affect the packet delivery properties of the communication link when the link is subjected to large temporal variations (as seen in Figure 31) so the poor energy efficiency is likely to be a result of insufficient link budget causing multiple packet retransmissions. Surprisingly, ATPC outperforms AMC-TPC when the link is subjected to large temporal variations, despite the latter being optimised for the dynamic link conditions experienced in healthcare applications rather than the pseudo-static scenarios considered in the optimisation of ATPC. Further analysis of the traces show that this is the result of ATPC being more agile than AMC-TPC so can react quicker to the changing channel conditions. The author believes this is a result of ATPC using a dynamic TPC algorithm which is more agile than the binary approach used in AMC-TPC.

Comparing the performance of HTPC to ATPC and AMC-TPC when the network is subjected to large temporal variations, the performance of HTPC can be seen to be vastly superior in terms of energy efficiency and packet delivery. When the network was subjected to large fluctuation and disturbance temporal variations, HTPC only consumed 4.5% more energy than when the optimal TP is considered whilst still maintaining a PRR > 99%. Similar performance was observed when the experimental WSN was subjected to large continuous temporal variations from a smart energy wireless network, with a PRR > 98% and the energy consumption being within 8.8% of the optimal level. The results show that HTPC is adaptive to link quality changes and can accurately predict the optimum TP even when the link quality is highly dynamic.

From Table 9 HTPC can be seen to outperform other SoA TPC protocols. The average energy consumed by links implemented with HTPC was 18% and 39% lower than links optimised with ATPC and TPC-WBAN, respectively. On top of this, HTPC did not detrimentally affect the communication reliability and achieved a PRR > 98% across all test environments. Both ATPC and TPC-WBAN detrimentally affected the communication reliability, with up to 15% of packets being dropped. HTPC closely matches the performance of the communication link when the optimum TP is considered, with the average energy consumed by links implemented with HTPC only 7.8% higher than the optimal performance.

Ideally, a quantitative comparison with several more existing TPC protocols would be carried out and the evaluation would extend beyond the energy efficiency and packet delivery performance. However, the results presented in other works are application dependent so a direct comparison cannot be made. Previous works have provided insufficient information on the protocol implementation so it has been impossible to replicate the protocols to perform an offline computation. As has been suggested in previous works ([17] [29]), a valuable contribution to this field would be defining a common test framework from which TPC protocols can be evaluated. From this, the energy efficiency, communication reliability and memory usage of different approaches could be compared for a common set of link conditions.

7.3 Comparison with Previous Works

In *2.1.6 Related Works*, a number of common deficiencies associated with current SoA TPC protocols were identified. The ways in which these aforementioned deficiencies have been addressed are as follows:

1. **Not practical to implement in WSN hardware.** HTPC requires few samples to be cached (10 bytes of data) and utilises simplistic metric evaluation techniques so is practical to implement on the resource constrained hardware. On top of this, it implements passive link monitoring and exploits existing network traffic to transport the link quality metrics so the energy overhead to implement HTPC is negligible.
2. **Poor accuracy.** HTPC captures more link quality properties than any other works on TPC. Through this, more of the energy critical properties can be accounted for and the TP can be more finely tuned to the current channel conditions.
3. **Poor tuning agility.** The link quality estimation technique implemented in HTPC utilises link quality metrics which can be computed over a single transaction so dynamic link conditions can be accounted for, even when channel throughput is minimal. On top of this, HTPC modulates the TP on a per-packet basis using a dynamic algorithm so is quick to react to changing channel conditions.
4. **Optimised for different objectives.** HTPC has been designed to address the most significant resource constraint in WSNs; energy. The evaluation presented in *7.2 Quantitative Evaluation* shows that HTPC can significantly improve the energy efficiency of wireless communication activities in WSNs.
5. **Optimised for a single application**. HTPC has been optimised and tested over various link conditions which are representative of a large number of WSN applications.
6. **Based on theoretical study and simulation**. HTPC has been designed through a combination of theoretical and empirical study. Practical evaluations in *7.2 Quantitative Evaluation* show that HTPC is effective in real-world WSNs.
7. **Do not account for packet retransmissions**. HTPC uses the required number of packet retransmissions (RNP) metric to estimate the minimum channel gain. Through this, channel conditions experienced over the complete transaction are accounted for in the calculation of the optimum TP.

7.4 Summary

In this chapter the performance of HTPC has been evaluated using quantitative and qualitative approaches. The practical evaluation showed that HTPC outperforms current SoA TPC protocols and achieves significant energy savings whilst still maintaining a high level of communication reliability, even when the link conditions are highly dynamic. When subjected to various temporal variations, the average energy consumed by links implemented with HTPC was 38%, 18% and 39% lower than using the maximum TP, ATPC and AMC-TPC, respectively. HTPC closely matches the performance of the communication link when the optimum TP is considered, with the average energy consumed by links implemented with HTPC only 7.8% higher than the optimal performance. On top of this, HTPC was shown to be practical to implement on representative WSN hardware through requiring minimal number of samples and utilising simplistic metric evaluation techniques. A comparison between HTPC and current TPC protocols showed that HTPC addresses many of the common deficiencies associated with TPC protocols and therefore presents an incremental improvement on SoA TPC protocols.

Chapter Eight: Conclusion and Future Work

In this thesis a novel holistic transmission power control (TPC) protocol with the primary objective of increasing the energy efficiency of wireless communication activities in wireless sensor networks (WSNs) has been proposed, implemented and evaluated.

The following conclusions are drawn:

1. TPC protocols for WSNs with energy efficiency objectives are not well developed and all previously published works suffer from a number of common deficiencies. These deficiencies lead to poor energy efficiency and/ or detrimental effects to the communication reliability, and thus have limited the implementation of TPC protocols in WSN applications.
2. Hidden and exposed node issues can be exacerbated through the implementation of a TPC protocol, leading to detrimental effects to energy efficiency and communication reliability. These are primarily the result of the communication and carrier sense radii being supressed as a result of minimising the TP. The hidden and exposed node issues can be identified and mitigated through capturing the packet delivery properties of the communication link.
3. There are significant opportunities for TPC protocols in WSN applications. A mathematical model which compares transmission power (TP) against communication reliability and energy consumption was developed. Applying this model to state-of-the-art (SoA) radio hardware and parameter values from current WSN standards, the maximum energy savings were quantified at between 38-80% for links in the connected region and up to 66% for links in the transitional and disconnected regions. From this, previous assumptions that protocols and mechanisms, such as TPC, not being able to achieve significant energy savings at short communications distances have been disproven. This study showed that the greatest energy savings are achieves at short communication distances and under ideal channel conditions.
4. An empirical characterisation of wireless link quality in typical WSN environments was conducted to identify and quantify the spatial and temporal factors which affect radio and link dynamics. The results highlight that link quality in WSNs exhibits complex and dynamic tendencies which are contrary to simplistic deterministic models. Link quality must therefore be estimated online, in real-time, using resources internal to the network.
5. An empirical evaluation of raw link quality metrics for evaluating the channel quality, packet delivery and channel stability properties of the communication link was conducted. This study highlighted that using signal-to-interference-and-noise ratio (SINR) to capture the channel quality properties of the communication link is most suitable since; it has a detectable correlation to TP, has a large measurement range so can be compared against the configurable parameter over the full TP range and has a detectable correlation to PRR even when interference exists in the network. Although SINR does suffer from a considerable level of variance over the measurement window, especially when the interference and noise power is weak, the variance can be addressed using low computation, memory and energy overhead methods which are practical to implement on the resource constrained hardware.

This study also found that required number of packet retransmission (RNP) based estimators are most suitable for estimating packet delivery properties of the communication link. This is because they require less computation, fewer samples and can be calculated over smaller sampling windows when compared to PRR based metrics. On top of this, only RNP based estimators can assess the number of packet retransmissions.

An overview of the metrics used to capture channel stability properties highlighted that it is most practical to reuse the same link quality metrics used to assess other link quality properties so that the sampling overhead is minimised. Channel quality metrics were found to have the greatest dynamic range and are more agile so their use is recommended.

6. HTPC has been proposed to increase the energy efficiency of wireless communication activities in WSNs. HTPC is adaptive to link quality changes through utilising agile link quality metrics, a dynamic tuning algorithm and TP updates on a per-packet basis. The optimal TP is estimated through combining channel quality and packet delivery properties to provide a real-time estimation of the minimum channel gain, and using the channel stability properties to implement an adaptive fade margin.
7. Practical evaluations show that HTPC is adaptive to link quality changes and outperforms current TPC protocols by achieving higher energy efficiency without detrimentally affecting the communication reliability. When subjected to several common temporal variations, links implemented with HTPC consumed 38% less than the current practise of using a fixed maximum TP and between 18-39% less than current SoA TPC protocols. Through offline computations, HTPC was found to closely match the performance of the optimal link performance, with links implemented with HTPC only consuming 7.8% more energy than when the optimal TP is considered.
8. Real-world implementations of HTPC show that it is practical to implement on the resource constrained hardware as a result of implementing simplistic metric evaluation techniques and requiring minimal numbers of samples. Comparing the performance and characteristics of HTPC against current TPC protocols, HTPC addresses the common deficiencies associated with current TPC protocols and therefore presents an incremental improvement on SoA TPC protocols.

8.1 Future Work

By means of future work, the following areas are proposed:

- **Common test framework**. Since the performance of a TPC protocol is heavily influenced by the environment and radio hardware, a quantitative evaluation between different solutions is a significant challenge. As was identified in *7.2 Quantitative Evaluation* and [17], a valuable contribution to this field would be defining a common test framework from which TPC protocols can be evaluated. Using this, the energy efficiency, communication reliability and memory usage of different approaches could be compared for a common set of link conditions.
- **Online evaluation with other TPC protocols**. In this work HTPC has only be compared against two current TPC protocols through an offline computation. Ideally, a quantitative comparison with several more existing TPC protocols would be carried out and the tuning metrics would be calculated empirically rather than theoretically. However, previous works have provided insufficient information on the protocol implementation so it has been impossible to replicate current solutions. It is proposed that contact is made with the authors of previous works to gain further insight of protocol implementation and identify if collaborative partnerships could be established to evaluate the different approaches.
- **The application of HTPC in emerging wireless standards**. Current WSN standards have primarily been designed and optimised to communicate over a distance of tens or hundreds of metres and have typically used frequency shift keying (FSK) modulation techniques and high data rates [1]. A number of emerging standards such as LoRa [82] and Sigfox [83] are being proposed in WSNs to communicate over very large distances (several kilometres). To enable this, ultra-narrow band modulation techniques (e.g. D-BPSK) and low data rates (e.g 100 bps) are being used [82]. The link conditions experienced by these networks will be significantly different than those presented by traditional WSNs. For example, the over-air transmission time will be significantly longer due to the low data rate so the probability that temporal factors will change the link quality over the transmission window is higher. An empirical study of link quality when considering different TPs in LoRa and Sigfox networks would be the first step towards determining the feasibility of using HTPC in these emerging wireless standards.
- **Co-existence with other protocols**. A common viewpoint that has been shared across multiple studies is that wireless networks need to collectively adapt transmission power, data rate and channel assignment to enhance throughout, minimise energy usage and maintain quality of service [29]. When these protocols are implemented, the receiver performance is likely to change. For example, the receiver sensitivity is likely to change when data rate control protocols are implemented. There is little previous study on how TPC protocols work in collaboration with data rate control and other similar protocols. A valuable contribution to this field would be to characterise how these protocols co-exist.
- **The implementation of HTPC in existing standards**. In this work a standard and hardware agnostic protocol has been developed. To simplify the implementation of HTPC into existing

standards (such as; ZigBee, Bluetooth Low Energy and WirelessHART), standard specific user manuals and libraries need to be created.

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Appendices

Appendix 1: Taxonomy of state-of-the-art radio hardware commonly used in WSNs

Radio hardware	Wireless sensor node usage	Transmission power range (dBm)	E_{elec} (nJ/bit)	E_{conn_max} (%)
Atmel AT86RF230	AVR Raven (Atmel), Iris (Crossbow), ZigBit ZDM-A1281 (Meshnetics).	-17 to 3	114.0	42.4
Chipcon CC1000	BTnode rev3 (Imperial College London), Mica2 (Crossbow), Spec (University of California).	-20 to 10	207.0	80.1
Chipcon CC2420	AcquisGrain (Phillips Research), BSN Node V2/3 (Imperial College London), ENS (University of Edinburgh), iMote2 (Crossbow), LEAP (University of California, Los Angeles), MicaZ (Crossbow), Kmote-B (InTech Co), Shimmer (Intel), Telos (University of California, Berkeley/ Moteiv), TelosB (Crossbow).	-25 to 0	112.2	51.1
Nordic Semiconductor nRF2401	DSYS24 (University College York), Hogthrob (Technical University of Denmark), Tyndall Mote (Tyndall).	-20 to 0	45.4	38.0
Nordic Semiconductor nRF903	CIT sensor node (Cork Institute of Technology), Fleck 1/2 (CSIRO).	-8 to 10	722.7	47.9
Texas Instruments CC1101 (Anaren A1101R08a)	WiSense (WiSense Technologies)	-30 to 12	187.2	70.8

Table 10. *Taxonomy of state-of-the-art radio hardware typically used in wireless sensor networks.*