Hughes, Jack Bryan, Lazaridis, Pavlos, Glover, Ian and Ball, Andrew

An Empirical Study of Link Quality Assessment in Wireless Sensor Networks applicable to Transmission Power Control Protocols

Original Citation

Hughes, Jack Bryan, Lazaridis, Pavlos, Glover, Ian and Ball, Andrew (2017) An Empirical Study of Link Quality Assessment in Wireless Sensor Networks applicable to Transmission Power Control Protocols. In: LAPC 2017, 13-13 November 2017, Loughborough, UK.

An Empirical Study of Link Quality Assessment in Wireless Sensor Networks applicable to Transmission Power Control Protocols

J B Hughes[†]*, P Lazaridis[†], I Glover[†], A Ball[†]

* Smart Component Technologies Ltd, Sheffield, Jack.Bryan.Hughes@gmail.com, [†]Centre for Efficiency and Performance Engineering research group, University of Huddersfield, United Kingdom.

Keywords: Path loss, Spatio-temporal Factors, Transmission Power Control, Wireless Link Quality, Wireless Sensor Networks.

Abstract

Transmission Power Control (TPC) protocols are poised for wide spread adoption in Wireless Sensor Networks (WSNs) to address energy constraints. Identifying the optimum transmission power is a significant challenge due to the complex and dynamic nature of the wireless transmission medium and this has resulted in several previous TPC protocols reporting poor reliability and energy efficiency in certain scenarios. In line with current studies, this study presents an empirical characterisation of the transmission medium in typical WSN environments. Through this, the sources of link quality degradation are identified and extensive empirical evidence of their effects are presented. The results highlight that low power wireless links are significantly affected by spatio-temporal factors with the severity of these factors being heavily dependent on environment.

1 Introduction

With the integration of sensing, processing and communication abilities in small form factor devices, wireless sensor networks (WSNs) are deployed in a variety of environments, supporting industrial automation, healthcare and smart energy applications [1]. These systems of smart sensors and actuators have revolutionised a wide array of application areas by providing an unprecedented density and fidelity of instrumentation. However, they present system challenges because of resource constraints, uncertainty, irregularity, mobility and scale [2].

One of the most significant resource constraints in WSNs is energy [3]. Energy constraints are the result of cost and form factor requirements limiting the type, size and capacity of the battery store. With significant energy constraints imposed on the networked devices, there is a growing need to optimise common activities through energy efficiency algorithms and protocols to prolong the lifetime of the networked devices. Previous studies have found that wireless communication is often the most energy consuming task that a WSN node performs [4].

One such protocol that has gained significant attention in recent research works but has yet to have a formal definition in a WSN standard, is transmission power control (TPC). TPC is the intelligent selection of transmission output power in a wireless communication system and has been shown in several research works to significantly reduce the energy consumption of wireless communication activities. For example, energy savings of up to 80% were reported in [5]. Through the implementation of a TPC protocol, communication can be carried out at the minimum energy cost, i.e. nodes dissipate the exact amount of energy to reach the intended recipient with high probability of successful reception. 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 as a result of the complex and dynamic nature of the transmission medium. Previous empirical studies (such as [6][7][8]) have shown that the propagation of radio signals are affected by several factors that contribute to the degradation of its quality. The effects of these factors are even more significant on the propagation of wireless signals with low-power radios, such as those used in WSNs. Consequently, radio links in WSNs are often unpredictable. In fact, their quality fluctuates over time and space, and connectivity is typically asymmetric [9].

Although previous studies have commonly argued that link quality exhibits complex and dynamic tendencies as a result of spatial and temporal factors, these studies often present contradictory results on the magnitude of these effects. This is because they were carried out using different hardware platforms having different radio ICs, different operational environments (e.g. indoor, outdoor) and experimental settings (e.g. traffic load, channel, packet acknowledgement and retransmission schemes). It is therefore necessary to analyse wireless link quality in typical WSN environments with current state-of-the-art and commonly used radio hardware in order to draw suitable conclusions upon which a TPC protocol can be designed. The main contribution of this work is the presentation of extensive empirical results that profile how spatial and temporal factors, in the context of different transmission power levels, affect radio and link dynamics in typical WSN environments.

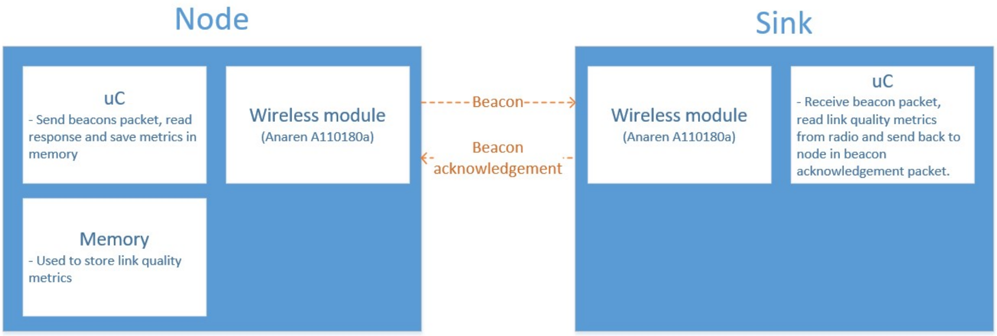


Figure 1. Experimental WSN block diagram

2 Characteristics of Link Quality in Wireless Sensor Networks

Communication link quality between low power sensor devices is affected by spatial and temporal factors. The spatial factors include surrounding environmental changes, such as terrain and communication distance. Temporal factors include surrounding environmental changes in general, such as interference from adjoining networks, shadowing from human activity and weather conditions. In this section, empirical results for investigation of these impacts in typical WSN environments are presented and from this a number of high level observations that will influence the design of a link quality estimator for a TPC protocol are formulated.

To assess link quality, the Receive Signal Strength Indicator (RSSI) metric is used. RSSI is a measurement of the power present in the received radio signal, which is averaged over eight symbol periods of each incoming packet [10]. To generate this metric, an experimental WSN was created. The nodes were connected to the sink using a single hop, star network topology. Both the nodes and sink use an Anaren A1101R08A radio module which is based on the Texas Instrument (TI) CC1101 chipset. This module was chosen because it has a large transmission power range (-30dBm to 12 dBm), good transmission power granularity (total of 32 levels), allows for easy retrieval of link quality metrics and closely represents the performance of the commonly used WSN hardware [11].

The basic operation of the experimental WSN is presented in Figure 1. The node and sink are placed 0.5m above the ground at different locations, maintaining the same antenna direction. The node sends out 100 beacon packets (at a rate of 500 packets per second) at each transmission power level and the generated link metrics, which are retrieved from the received beacon packets, are saved in local non-volatile memory on the node, ready to be downloaded and analysed. 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 influence the result.

2.1 Spatial Characteristics

To assess and quantify the spatial impact, a study into the correlation between transmission power and RSSI was carried out in three environments which are representative of WSNs. The test environments were chosen to be a grass field, an office and a warehouse, to represent WSN environments in a range of applications including; smart energy, environmental monitoring and industrial automation.

The results from one node/ sink pair in the three test environments are shown in Figure 2. Each curve demonstrates the correlation between transmission power and RSSI at a certain communication distance. The confidence intervals (95%) were calculated to show the variance in the measured parameter over the measurement window but due to the stable performance of RSSI, the confidence intervals are negligible so they have not been included in Figure 2. The results can be summarised by the following high-level observations:

(1) **An increase in communication distance does not always result in a decrease in received power**. As per the Friis free-space path loss model (Eq. 1) the received power (P_r) decays as a function of the communication distance (d) raised to the power two (i.e. a power law function). Our results show that the slopes of the RSSI curves generally decrease as the communication distance increases, but this is not always the case. For example, in Figure 2b, the RSSI was on average 3dB higher at a communication distance of 19m compared to that at 15m. 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, resulting in the receiver seeing a superposition of multiple copies of the transmitted signal that lead to constructive and destructive interference at the receiver.

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2} \quad (1)$$

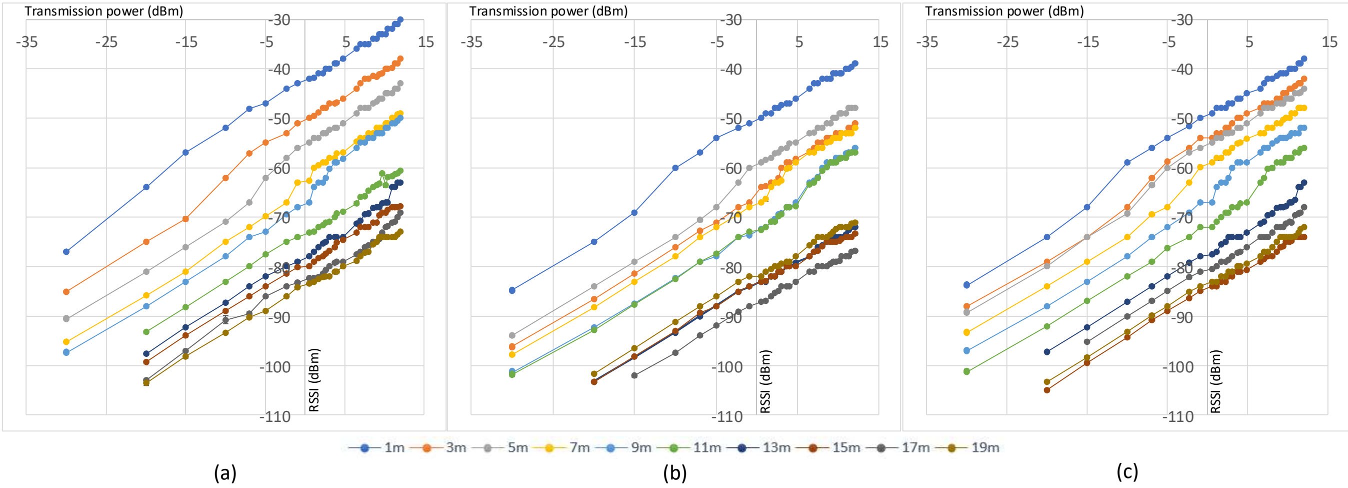


Figure 2. Transmission power against RSSI for grass field (a), office (b) and warehouse (c) environments.

(2) **The relationship between communication distance and received power is environmentally dependent**. The curves showing the relationship between RSSI and communication distance are significantly different for the three test environments. For example, at a communication distance of 3m and using a transmission power of 12dBm, the RSSI is -37dBm for the grass field environment, -52dBm for the office environment and -42dBm for the warehouse. This is the result of the different environments presenting unique sets of propagation paths which attenuate the transmitted signal in vastly different ways.

These observations confirm findings from previous works, such as the quality of radio communication between low power sensor devices varies significantly with environment. The analysis has also gone further than previous works and observed the characteristics of RSSI in multiple WSN environments when different transmission power levels are considered and state-of-the-art, commonly used radio hardware is used.

2.2 Temporal Characteristics

The dynamic nature of the transmission medium was characterised through empirically profiling the temporal variations of the transmission medium. Basic observations of the chosen test environments highlight that there are multiple potential sources of temporal variation. As documented by Lin et al. in [12], these variations can be categorised into three patterns:

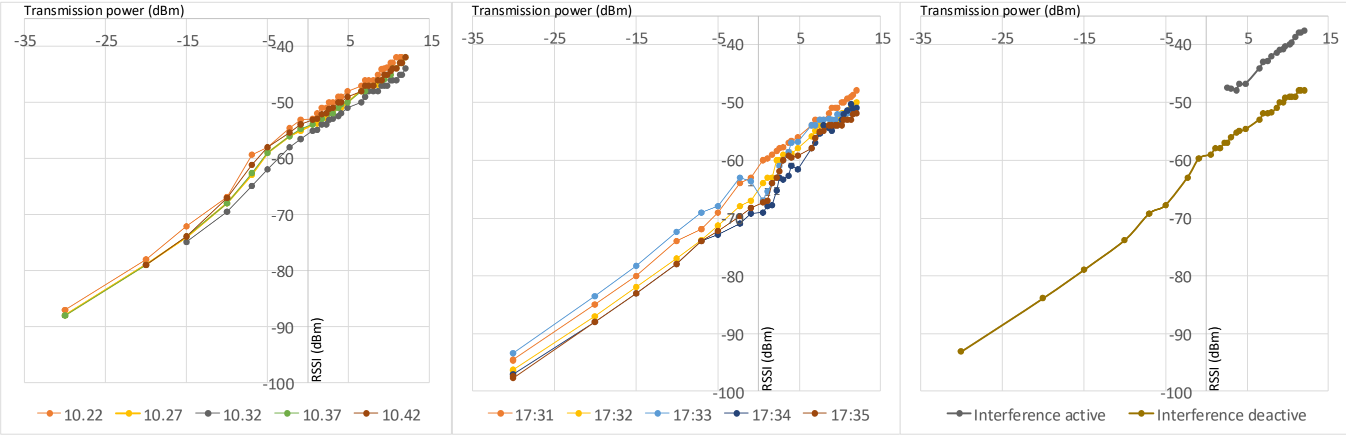
1. **Small fluctuations**. Small fluctuations are the result of multipath fading and changes in temperature and humidity.
2. **Large fluctuations and Disturbances.** Large fluctuation and disturbance temporal patterns are typically caused by shadowing and fading effects of humans, moving doors and other objects.
3. **Continuous large fluctuations.** Continuous large fluctuations are the result of interference from high-bandwidth, high transmission power 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 variation patterns were observed over the three test environments.

2.2.1 Small Fluctuations

To monitor small fluctuation temporal patterns, a 72-hour experiment in a grass field environment was conducted. This environment was chosen because it was likely to be subjected to temperature and humidity changes. Figure 3a presents our empirical data obtained from the node placed at 5m from the sink. Each curve represents the correlation between transmission power and RSSI at a specific time, over a twenty-minute period where the greatest variance in RSSI was observed.

The results from the grass field environment show that the receive signal strength changes slowly but noticeably over time. As seen in Figure 3a, the maximum change in RSSI over a 5-minute time window is 4dB. Comparing this temporal fluctuation to the weather forecast, it was found that the test site received heavy rain between 10.30 and 10.35am. During this time, the received signal strength was lower which is thought to be attributed to two phenomena. The first is rain fade, i.e. increased atmospheric absorption because of increased water vapour. The second, and more likely, cause of this temporal variation is an increased reflective path signal strength leading to increased destructive interference at the receiver.



(a) (b) (c)

Figure 3. Transmission power against RSSI showing small fluctuation (a), large fluctuation and disturbances (b) and continuous large fluctuation (c) temporal patterns.

According to the two-ray path model (Figure 4), the signal at the receiver is a combination of a line-of-sight (LOS) and non-line of sight (NLOS) ground reflected signal path. At the receiver they will lead to either constructive or destructive interference depending on the communication distance (d), wavelength (λ) and antenna elevation of the transmitter and receiver (h_t and h_r respectively) as described by Eq. 2. Applying Eq. 2 to the application (d=5m, f=868MHz, ht and hr = 0.5m), the reflective path will be 51.9^0 out of phase which would result in destructive interference at the receiver and a lower received signal strength.

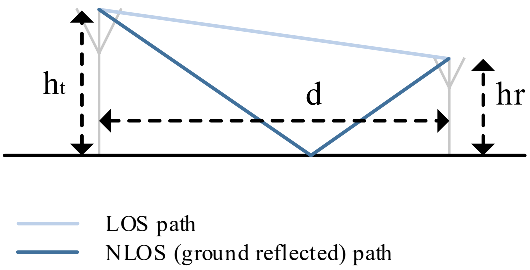


Figure 4. Two-ray path model.

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

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 which in turn leads to a lower received signal strength at the receiver.

As seen in Figure 3a, the received signal strength is still lower after the rain shower finishes so this temporal effect is more than likely the result of increased ground conductivity leading to higher destructive interference at the receiver as only when the ground dries a number of minutes after the rain shower finishes, the received signal strength return to its pre-rain performance.

2.2.2 Large Fluctuations and Disturbances

To observe the large fluctuations in link quality caused by shadowing effects of humans and other moving objects, an 1-hour experiment was conducted in a warehouse environment. The nodes were configured to transmit beacon frames at shorter time periods than in 2.2.1, to capture the temporal factors which may occur over very short time periods (e.g. human presence in the network area). The results for a 5-minute window which showed the highest levels of temporal variation are presented in Figure 3b. During the measurement window, the RSSI can be seen to change by up to 6dB over small time periods. Correlating the data with visual observations of the test environment, these large changes in RSSI were seen to be caused by human presence and moving machinery obstructing the LOS communication path.

The relationship between RSSI and transmission power can be seen to be less linear and has higher variance than the results presented in Figure 3a (small fluctuation temporal patterns). This is believed to be caused by the temporal factors changing over the measurement window. For example, the measurement window is typically around 6 seconds, which is larger than the time period of some of the temporal fluctuations (e.g. human walking across the direct line-of-sight communication path).

2.2.3 Large Continuous Fluctuations

In the office environment, continuous large fluctuation patterns were observed over time. This temporal pattern was attributed to a smart energy meter which was located within 3m of the receiving node and operating at the same channel frequency. The relationship between RSSI and transmission power with the interferer active and deactivate is presented in

Figure 3c. Results show that the relationship between RSSI and transmission power is significantly affected by large continuous temporal patterns caused from an adjoining network operating in the same frequency band. When the adjoining network is active, the RSSI is on average 10dB higher. This is the result of RSSI following an additive model and thus representing the sum of all input powers (i.e. input power of both signal of interest and background noise). Therefore resulting in external interference increasing the receive signal strength due to increased background noise. As seen by the limited number of data points representing the curve for when interference is present in the network, external interference also detrimentally effects the communication reliability. This highlights that the relationship between RSSI and communication reliability is not fixed and TPC protocols such as [8][14][15] that assume this, would lead to unreliable performance when these temporal patterns exist in the network.

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; transmission power, 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 that they can significantly affect the relationship between RSSI and transmission power.

4 Conclusion

Through the considered test methodologies and a rigorous statistical analysis of the received power, the spatial and temporal characteristics of the transmission medium in typical WSN environments were 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 allow the models which are used to design and validate link quality estimators for TPC protocols to be re-evaluated and updated to ensure reliable and energy efficient performance over a wide variety of scenarios.

Acknowledgements

The authors would like to thank Smart Component Technologies Ltd, Sheffield, for facilitating and funding this work.

References

[1] A. Chandrakasan and et. al, "Design considerations for distributed microsensor systems", *Proc. of the IEEE Conf. on Custom Integrated Circuits,* San Diego, USA, (1999).

[2] J. Yick, B. Mukherjee, D. Ghosal. "Wireless sensor network survey", *Computer Networks: Int. Jounal of Computer and Telecommunications Networking*, **vol. 52**, pp. 2392-2330, (2008).

[3] C. Buratti, A. Conti, D. Dardari, R.Verdone. "An overview of wireless sensor networks technology and evolution," *Sensors, special issue "Wireless Sensor Technologies and Applications"*, **vol. 9**, pp. 6869-6896, (2009).

[4] L. Correia, D. Macedo, A. Santos, A. Loureiro, J. Nogueira, "Transmission power control techniques for wireless sensor networks," *Computer Networks: Int. Jounal of Computer and Telecommunications Networking,* **vol. 51**, pp. 4765-4779, (2007).

[5] J. B. Hughes, P. Lazaridis, I. Glover and A. Ball, "Opportunities for transmission power control Protocols in wireless sensor networks", *Submitted to the 23rd Int. Conf. on Automation and Computing*, Huddersfield, UK, (2017).

[6] N. Baccour et. al. "Radio link quality estimation in low-power wireless networks", (Springer Press, London, 2013).

[7] G. Zhou, T. He, S. Krishnamurthy, J. Stankovic, "Impact of radio irregularity on wireless sensor networks", *Proc. 2nd Int. Conf. on Mobile Systems, Applications and Services*, Boston, USA, (2004).

[8] S. Lin, J. Zhang, G. Zhou, L. Gu, T. He, J. Stankovic, "ATPC: adaptive transmission power control for wireless sensor networks", *Proc. of the 4th Int. Conf. on embedded network sensor systems (SenSys)*, Colorado, USA, (2006).

[9] D. B. Smith, L. W. Hanlen, D. Miniutti, "Transmit power control for wireless body area networks using novel channel prediction", *Proc. IEEE Wireless Communications and Networking Conf.: PHY and Fundamentals*, Shanghai, China, (2012).

[10] Texas Instruments, "CC2420 datasheet", *http://www.ti.com/lit/ds/symlink/cc2420.pdf*, accessed April 2017.

[11] Texas Instruments, "CC1101 datasheet", *http://www.ti.com/lit/ds/symlink/cc1101.pdf*, accessed May 2017.

[12] S. Lin, G. Zhou, K. Whitehouse, Y. Wu, J. Stankovic, T. He. "Towards stable network performance in wireless sensor networks", *Proc. of the 30th IEEE Real-Time Systems Symposium Conf.,* Washington, USA, (2009).

[13] D. Ke-Lin, M. Swammy. "Wireless communication systems – From RF subsystems to 4G enabling technologies" (Cambridge University Press, Cambridge, 2010).

[14] L. Correia. "Transmission power control techniques for MAC protocols in wireless sensor networks", *Proc. Network Operations and Management Symposium,* Salvador, Brazil, (2008).

[15] W. Lee, B. D. Lee, N. Him, "Hybrid transmission power control for wireless body sensor systems", *Int. Journal of Distributed Sensor Networks*, **vol. 10**. pp 1-9, (2014).