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A Survey of Link Quality Properties Related to Transmission Power Control Protocols in Wireless Sensor Networks

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Abstract— **Transmission Power Control (TPC) protocols are poised for wide spread adoption in wireless sensor networks (WSNs) to address energy constraints. The link quality properties that need to be captured in order to identify the optimum transmission power (TP) have not been clearly defined and previous works have presented conflicting views on the matter. This has led to several current TPC protocols using vastly different link quality properties and reporting unreliable, unstable and inefficient network performance. In this work, observations from several empirical studies on low-power wireless links are applied to identify the most critical properties of link quality for a TPC protocol. Comparing the requirements against currently available link quality estimators, it is shown that link quality estimation in WSNs is still very much an open challenge and one that must be addressed in order to implement an accurate and reliable TPC protocol.**

Keywords; Link Quality Estimation, Link Quality Properties, Transmission Power Control, Wireless Sensor Networks.

I. INTRODUCTION

Wireless sensor networks (WSNs) are fundamentally constrained in energy, memory and computational complexity due to cost and form factor requirements [1]. WSNs therefore require lightweight, in terms of memory and computational complexity, and energy efficient protocols and mechanisms to enable these systems of smart sensors to run for arbitrary long time periods (i.e. years) without battery replacement or recharging. Previous works have found that wireless communications is typically the most energy consuming task that a WSN node performs [2], resulting in the optimisation of this activity being seen as pivotal in order to achieve battery life requirements.

A large number of research 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 [3], packet routing [4] and duty cycle [5]. Some of the most promising works look at modulating the transmission power (TP) to reduce the number of packets sent with excessive power for the intended recipient and the number of packet retransmissions. This technique is commonly referred to as Transmission Power Control (TPC).

Previous works have shown that TPC protocols are able to achieve significant energy savings. As quantified in “unpublished” [6], modulating the TP can reduce the energy consumed by communication activities by up to 80% for links that exist in the connected region and 66% for links that exist in the disconnected region. On top of this, previous works have reported improvements to spectrum efficiency and packet delivery as a result of interference suppression and minimising the bit error rate through ensuring sufficient link budget. Although no current WSN standards include a formal definition of a TPC protocol [7], several do feature support for it and it is widely recognised that modulating the TP is a key requirement for implementing reliable and energy efficient operation so it’s adoption is likely to increase significantly in the forthcoming years.

In order to identify the optimum TP, the wireless link quality needs to be continually evaluated. This process is known as link quality estimation. Link quality estimation consists of evaluating a metric, a mathematical expression, within an estimation window (e.g. at each w seconds or based on w received/ sent packets), to quantify the quality of a wireless communications link [8]. The generated metric is known as a link quality estimator (LQE). As highlighted in [9], a LQE can estimate quality on the basis of multiple properties, including; packet delivery, asymmetry, stability, channel quality, channel load and location.

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 [8]. 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 link quality estimator are heavily dependent upon the protocol or mechanism it is proposed to be used in and the resources available in the network [9].

The main contributions of this paper are as follows:

- Analysis of the deficiencies associated with the link quality estimation process used in TPC protocols for WSNs.

- Identification and justification of the most suitable link quality properties that need to be captured for a TPC protocol.

The rest of this paper is organised as follows: the motivation behind this work is explained in section II, the deficiencies associated with the link quality estimation process implemented in current TPC protocols is presented in section III, the link quality properties that need to be measured are identified and justified in section IV, a comparison between the LQE requirements for a TPC protocol and currently available LQEs is presented in section V and conclusions are drawn in section VI.

II. MOTIVATION

Previous empirical studies (such as [9] [10] [11]) 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 [12]. As documented in several previous studies (such as [11] and [13]), theoretical modelling through using simulators and analytical models cannot be directly employed in WSNs since the wireless environment changes dynamically. Even if the changes are relatively slow, deterministic models require physical layer information such as terrain information and coherence time of the channel. Such data is generally inaccessible or even unavailable to the high layer protocol. As a result of the properties of WSN nodes (namely; limited memory size, low power and low computational complexity) and dynamic network conditions, there is a requirement for link quality to be estimated online, in real-time, using resources internal to the network.

There is wide spread debate about what link quality properties need to be captured in order to accurately determine the optimum TP. This has resulted in previous works on TPC using several different link quality properties, with all reporting various deficiencies. We believe it is a direct result of these deficiencies that has prevented TPC protocols from having wide spread adoption in WSNs and therefore addressing them is of significant importance.

In general, the more link quality properties that an LQE can represent, the finer grain link classification 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 computational 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.

III. DEFICIENCIES ASSOCIATED WITH THE LINK QUALITY ESTIMATION PROCESS USED IN CURRENT TPC PROTOCOLS

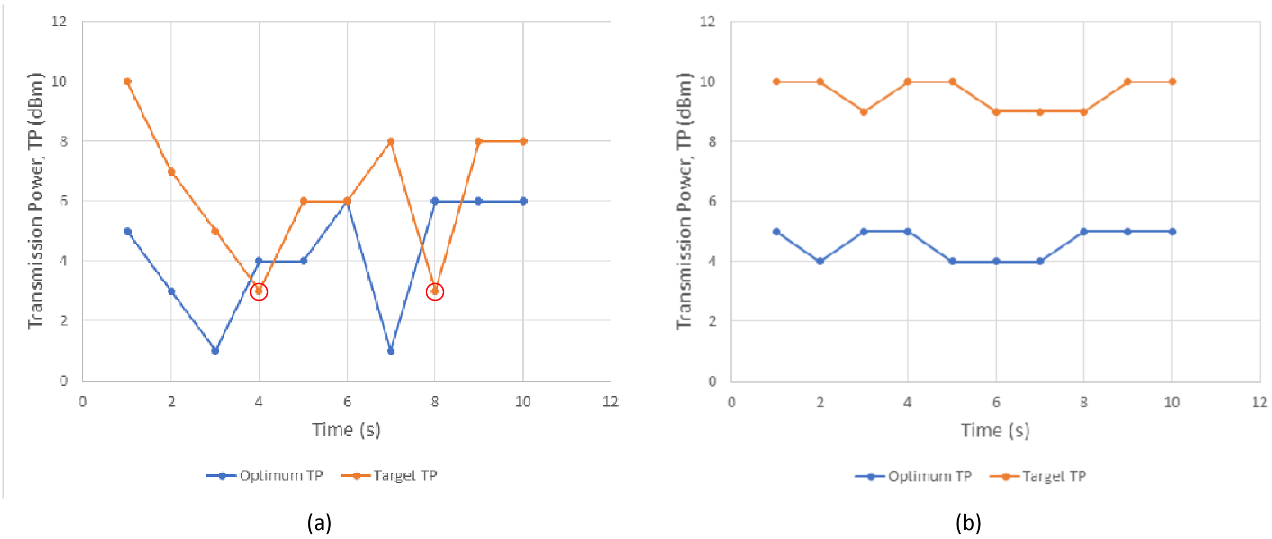
Analysis of the link quality properties captured in previously published works on TPC in WSNs, including: ATPC [11], B-MAC-PCI [14] B-MAC-PCA [14], ATPC for WBANs [15], TPC in WBANs for healthcare monitoring [16], AMC-TPC [7], RSSI/LQI TPC for BANs in healthcare environments [17] and Hybrid [18], highlight that all current solutions suffer from one or more of the following major deficiencies:

1) Unable to identify when multiple retransmissions occur. Packet retransmissions, as a result of poor communication reliability, consume significant energy resources. Protocols such as Hybrid [18] and ATPC [11] only capture the channel quality properties so are unable to identify whether the measurements used to quantify the channel quality properties took multiple retransmissions to obtain.

2) Tuning accuracy. Protocols such as ATPC [11] and B-MAC-PCA [14] which do not capture the channel stability properties are unable to benefit from the fact that the TP can be finely tuned to the calculated optimal level without significant risk to detrimental network performance when the link is stable. This observation is further explored in section IVA.

3) Tuning agility. Protocols such as B-MAC_PCI [14] are unable to provide a quantitative assessment between the received signal and the configurable parameter (in this case TP) so a linear algorithm has to implemented. As documented in [18], linear algorithms adapt the TP using reactive means over large time periods which significantly reduces the agility of the protocol leading to poor energy efficiency and/ or poor communication reliability. If channel quality properties are monitored, dynamic algorithms can be applied which, as highlighted in [18], yield the optimal performance.

4) Unable to identify and mitigate against hidden and exposed node issues. In [19], it was highlighted that the exposed and hidden node issues are exacerbated when TPC protocols are applied and result in detrimental effects on communication reliability and channel throughput. Identifying when these phenomena occur and mitigating against them was deemed necessary. These phenomena can only be identified if the packet delivery properties of the communication link are monitored so protocols such as AMC-TPC [7] and Hybrid [18], could result in unstable and unreliable network performance when the hidden and exposed node issues occur.



9p-Figure 1, Optimal and target TP using a fixed TP margin for low stability (a) and high stability (b) links

IV. PROPOSED LINK QUALITY PROPERTIES FOR A TPC PROTOCOL

To overcome the deficiencies outlined in section III, we propose the combination of multiple link properties to get a holistic characterisation of the link quality. Based upon observations from previous works on TPC and empirical studies on link quality in WSNs, the capture of the following link quality properties are proposed for a TPC protocol.

A. *Channel Quality*

Channel quality represents properties of the received signal. The most common properties that are captured by channel quality 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 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 case TP, and the resulting received signal. Secondly, channel quality properties allow for a link quality threshold (LQT) to be generated. Many previous dynamic TPC protocols (including [11] [15] [16]) have configured the TP based on an analysis between the current channel quality and a target channel quality, otherwise known as the LQT. The LQT is the value of the channel quality property that is believed to yield the highest energy efficiency, i.e. high probability of successful packet transmission with little excess power at the receiver.

B. *Packet Delivery*

Packet delivery is the capacity of the link to successfully delivery data and is sometimes referred to as the communication reliability. Packet delivery properties need 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 TP 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. To ensure that communication is being carried out at the lowest energy cost (i.e. with no packet retransmissions), it is essential for the packet delivery properties of the link to be monitored.

3) Mitigate against the exposed and hidden node problems. The effects of the exposed and hidden node problems can be mitigated through monitoring the packet delivery properties, thus allowing the TP to be increased to leverage the capture effect or bring the interfering transmitter within the carrier sense range.

C. *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 channel variance between the two windows. Channel stability gives a measure of how similar the performance of the network is likely to be over the operational window compared to the estimation window.

For links with low variance (and hence high stability), the perceived performance of the network is likely to be very similar in the estimation and operational windows so the LQE should be a good representation of the actual channel conditions. This subsequently allows the TP to be finely tuned to the calculated optimal level (i.e. target TP $\approx$ 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 finely tuning the TP to the calculated optimal level would increase the risk of performance degradation. The difference between the calculated optimum TP and the target TP is known as the TP margin. The adverse effects of using a fixed TP margin for communication links with low and high channel stability are shown in the example datasets in 9p-Figure 1a and 9p-Figure 1b, respectively.

As seen in 9p-Figure 1a, links with low stability and low TP margins can result in the TP being insufficient for successful packet reception. When the target TP is lower than the optimal TP (as shown with the red circled samples in 9p-Figure 1a), links will suffer from high energy usage (due to packet retransmissions) and communication reliability will be poor. On the other hand, when a large TP margin is used, the risk of detrimental network performance for links with low stability will be overcome but energy usage for links with high stability is unnecessarily high (as shown in 9p-Figure 1b).

As detailed in [15], to achieve optimum performance from both a reliability and energy perspective, a variable TP margin is required that reflects the channel stability (i.e. high stability links use a small TP margin and low stability links use a large TP margin). The performance of a variable TP margin is shown in Figure 2 for periods of low and high channel stability (red and green regions, respectively).

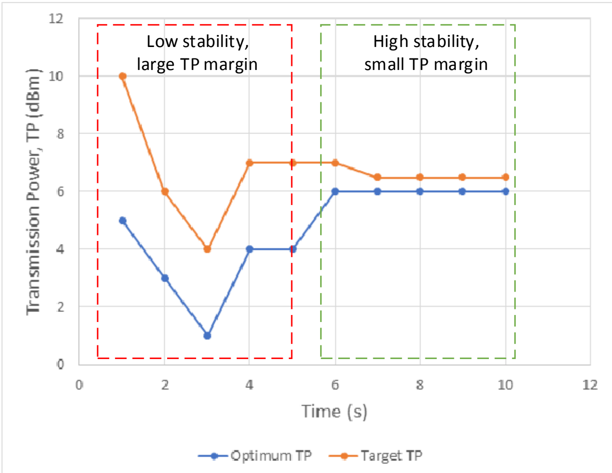


Figure 2, Optimal and target TP using a variable TP margin.

Other link properties, such as packet asymmetry and channel load, can be discarded for this application 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 typically 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 computational resources required for the link quality estimation process.

V. Comparison of Link Quality Estimators

Comparing currently available LQEs is a challenging task. One of the reasons for this is the impossibility, or at least the difficultly, to provide a quantitative evaluation of the accuracy of LQEs. In fact, in link quality estimation, there is a lack of a ground-truth metric in relation to which the accuracy of the estimators can be assessed. In classic estimation theory, an estimation process is 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 as the "real" one to represent link quality and that link quality is represented by quantities of different natures, since some estimators are based on packet retransmission count, whereas others are a hybrid and more complex.

The high-level characteristics of currently available LQEs presented in [9] have been analysed to determine their suitability for use in a TPC protocol. Through this analysis it was found that most of the currently available LQEs only capture single link properties so can only provide a partial characterisation of the communication link. For example, all packet reception ratio (PRR) and required number of packet retransmission (RNP) based software LQEs are only able to account for the packet delivery properties. 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 section IV, we advocate combining several link quality properties in order to capture a number of energy critical characteristics of the communication link. This renders these single property LQEs unsuitable for the proposed TPC protocol.

Comparing the link quality properties captured in common LQEs against the requirements of a LQE for a TPC protocol outlined in section IV, it was found that none of the currently available LQEs target all the properties which are proposed for a TPC protocol, namely; channel quality, packet delivery and channel stability. Both the channel state information and triangle metric [9] LQEs are able to account for channel quality and packet delivery properties but are unable to account for stability properties of link quality. The fuzzy link quality estimator (F-LQE) [8] is able to account for all the proposed link quality properties for a TPC protocol, as well as, channel asymmetry. However, as documented in [8], F-LQE requires high memory footprint and computational

VI. Conclusion

This paper has explored the link quality estimation process required in TPC protocols to identify the optimum TP. Applying observations from previous works on TPC in WSNs, the common deficiencies associated with the link quality estimation process were identified. Combining these deficiencies with observations presented in several empirical studies on low power wireless links, the state-of-the-art has been developed through the identification of the link quality properties that need to be captured to ensure efficient and reliable operation. Through comparing the LQE requirements for a TPC protocol against currently available LQEs, it has been shown that there is a requirement and subsequent opportunity, for a new LQE to evaluate the most energy critical properties of the communication link for a TPC protocol.

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