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# Opportunities for Transmission Power Control Protocols in Wireless Sensor Networks

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*Abstract*— **This study investigates the opportunities for transmission power control (TPC) protocols in resource constrained wireless sensor networks (WSNs). The paper begins by creating a generalised model to describe the relationship between transmission power, communication reliability and energy consumption. Applying this model to the performance of state-of-the-art radio hardware, the maximum potential energy savings achievable through the implementation of a TPC protocol are identified. From this, previous assumptions about the limited impact of protocols and mechanisms, such as TPC, which seek to reduce the energy consumed by wireless communication activities through targeting the distance dependent term are disproven. This paper concludes by presenting guidelines on the link conditions which offer the greatest opportunities for a TPC protocol.**

***Keywords- Radio Energy Modelling, Transmission Power Control, Wireless Sensor Networks.***

## I. INTRODUCTION

Wireless Sensor Networks (WSNs) are becoming widely adopted across multiple industries to implement sensor and control applications. These networks of smart sensors and actuators require energy efficient and reliable operation to meet application requirements. The proliferation of wireless technology is resulting in an ever increasingly crowded network space which makes realising these requirements a significant challenge. A common viewpoint which has been shared across multiple studies (such as [1]) is that wireless networks need to collectively adapt transmission power, modulation and channel assignment, to enhance throughput, minimise energy usage and maintain quality of service (QoS).

WSNs are subjected to regulatory body restrictions and have severe resource constraints which mandate the need for efficient spectrum management. Efficient utilisation of radio resources is up to the radio resource management strategy and several common protocols and mechanisms are typically implemented. These configure a wide array of radio parameters, including; data rate [2], duty cycle [3] and packet routing [4]. One protocol that has gained significant attention in previous works, but has yet to have a formal definition in a WSN standard, is transmission power control (TPC) [5].

TPC is the intelligent selection of transmission output power in a wireless communication system and can be used to improve several performance properties, including; energy efficiency, reliability and throughput. The most severe resource constraint in WSNs is energy [6] so TPC protocols which address this, are of most relevance. Through the implementation of a TPC protocol, communication can be carried out at a minimum energy cost. This is a result of packets being sent with just enough energy to reach the intended recipient with a low probability of a bit error, thus reducing the number of packets sent at an excessively high transmission power and the number of packet retransmissions.

The rest of this paper is organised as follows: the motivation behind this work is explained in section II, the radio energy model is presented in section III, the potential energy savings are quantified in section IV and conclusions are drawn in section V.

## II. MOTIVATION

Although 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 [7] maximum energy savings of up to 79% were reported, whilst in [6] 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 platforms having different radio chips (e.g. MicaZ that incorporates the Chipcon CC2420 used in [7] [8] [9], whilst the Mica2 with the Chipcon C1000 used in [10] [6]), different operational environments (e.g. indoor, outdoor) and different experimental settings (e.g. packet acknowledgement and retransmission schemes, different packet lengths, etc.).

To address the lack of ground truth about the potential energy savings of a TPC protocol, a generalised model to compare transmission power, communication reliability and energy consumption is formulated. Applying this model to the performance of commonly used, state-of-the-art radio hardware, the maximum energy savings for a range of scenarios are presented.

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 [11] highlighted that the distance independent term of $E_{bit}$ dominates the distance dependent term at short communication distances. 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 at short communication distances. In this paper, this previous assumption is contested through comparing $E_{bit}$ over a range of channel conditions and communications distances, when the nominal and maximum transmission power is used.

## III. RADIO ENERGY MODEL

### A. HCB Energy Model

To quantify the energy dissipated by the transmitting and receiving radios ($E_{Tx}$ and $E_{Rx}$), the first-order Heinselman-Chandrakasan-Balakrishnan (HCB) energy model [12] 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 ($\varepsilon_{amp}$), packet length ($k$), communication distance ($d$) and path loss exponent ($\alpha$), as seen in Figure 1 and (1) and (2).

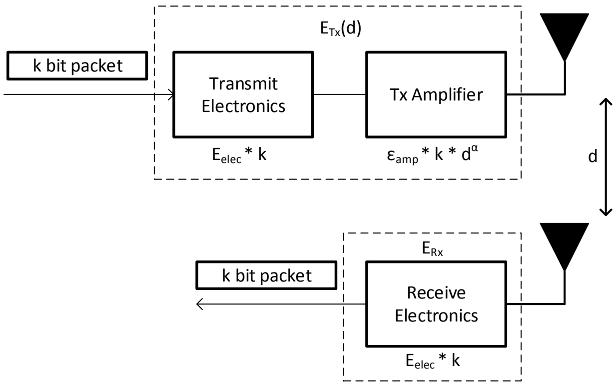


Figure 1, First order HCB energy model.

$$E_{Tx}(k,d) = E_{elec}k + \varepsilon_{amp}kd^{\alpha} \tag{1}$$

$$E_{Rx}(k) = E_{elec}k \tag{2}$$

In this paper, the following parameter values are used.

TABLE I. PARAMETERS FOR HCB MODEL

| Parameter | Value | Units |
|---|---|---|
| $E_{elec}$ | 50 | nJ/bit |
| $\varepsilon_{amp}$ | 0.1 | nJ/bit/m$^2$ |

These parameters are in line with state-of-the art radio design. For example, it is assumed that the radio dissipates 50nJ/bit to run the transmitter and receiver circuitry ($E_{elec}$). This is similar to the performance of the Nordic Semiconductor nRF2401 radio transceiver (1Mbps data rate radio that operates at 2.7V and consumes 16.8mA of current [13]) which has been extensively used in previous WSN nodes.

Assuming link layer acknowledgment and retransmission schemes are implemented, the energy dissipated per transaction[1] (assuming acknowledgement packets are always successfully received) is given by:

$$E_{trans} = n_{Tx}(E_{Rx} + E_{Tx}) \tag{3}$$

The number of packet transmissions required before a high probability of successful packet reception can be calculated using (4), where $P_a$ is the confidence interval (probability that after $n$ transmissions the packet will be successfully received, typically 99%) and $PRR$ is the packet reception ratio (probability that a single packet will be successfully received).

$$\eta_{tx} = \frac{\ln(1 - P_a)}{\ln(1 - PRR)} + 1 \tag{4}$$

Link layer protocols typically place limits of the maximum number of transmissions (i.e. $n_{Tx\_max}$). In this work it is assumed that this is 3 which is in line with link layer protocols typically used in WSNs, such as WirelessHART [14] and ZigBee [15]. The first order HCB model equations, (1) and (2), can be made packet length agnostic, by dividing through by $k$. The energy dissipated per bit ($E_{bit}$) is therefore:

$$E_{bit} = \frac{n_{Tx}(E_{Rx} + E_{Tx})}{k}$$
$$E_{bit} = n_{Tx}(E_{elec} + (E_{elec} + \varepsilon_{amp}d^{\alpha}))$$
$$E_{bit} = n_{Tx}(2E_{elec} + \varepsilon_{amp}d^{\alpha}) \tag{5}$$

### B. Generalised Energy Model

In order to evaluate $E_{bit}$ when different transmission powers are considered, (5) needs to be modified to represent the actual, rather than nominal, energy dissipated. As shown in (6), this can be achieved by substituting $\varepsilon_{amp}d^{\alpha}$ with $E_{TPx}$ (energy dissipated by the transmit power amplifier per bit when different transmission powers are considered).

$$E_{bit} = n_{Tx}(2E_{elec} + E_{TPx}) \tag{6}$$

Combining (6) with path loss ($PL$) (7), signal-to-noise ratio ($SNR$) (8) and $PRR$ (9) equations, a generalised model showing the relationship between transmission power, 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 (10) and (11), and shown graphically in

[1] A transaction is a data exchange event between a transmitter and receiver, and may consist of multiple packet retransmissions is a successful packet transmission is not detected (not acknowledged). Every transaction will consist of at least one packet transmission and reception.

Figure 2 for the Texas Instrument CC1101 radio at a communication distance of 50m and a path loss exponent of 2.

$$PL = 10_{\alpha}\log_{10}(F) + 10_{\alpha}\log_{10}(d) - 30\alpha + 32.44 \tag{7}$$

$$SNR = P_t - PL - P_n \tag{8}$$

$$PRR = \left(1 - \frac{1}{2}e^{\frac{SNR}{2}\frac{1}{64}}\right)^k \tag{9}$$

$$PRR = \left(1 - \frac{1}{2}e^{\frac{P_t - PL - P_n}{128}}\right)^k \tag{10}$$

$$E_{bit} = \left(\frac{\ln(1-P_a)}{\ln(1-PRR)} + 1\right) \times (2E_{elec} + E_{TPx}) \tag{11}$$


Figure 2, Generalised Energy Model.

### C. *Potential Energy Savings*

As seen in Figure 2, the transmission power that results in the minimum value of $E_{bit}$ exists on the boundary between the connected and transitional regions. At the optimum transmission power, packets are sent with just enough energy to ensure successful packet reception at the receiver with a low probability of a bit error. Figure 2 shows that it is preferable to use a slightly higher, rather than lower, transmission power because $E_{bit}$ increases much more rapidly and communication reliability is detrimentally affected when the transmission power 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 transmission power thus ensuring that packets are not sent with excessive power for the intended recipient. Referring this observation to (6), 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. $PR\,R>95\%$). 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 ($E_{TP\_max}$) transmission power, as follows.

$$\begin{aligned} E_{bit\_min} &= 2E_{elec} + E_{TP\_min} \\ E_{bit\_max} &= 2E_{elec} + E_{TP\_max} \\ E_{conn\_max} &= \frac{E_{TP\_max} - E_{TP\_min}}{E_{TP\_max}} \end{aligned} \tag{12}$$

The maximum energy savings in the connected region are radio hardware dependent since the following parameters vary from device to device; transmission power 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 [16].

Communication links that exist in the transitional and disconnected regions can be improved from an energy and communication reliability perspective through increasing the transmission power. In these regions, $E_{bit}$ is dominated by $n_{Tx}$ as the difference in transmission power that results in a link residing in the connected or disconnected regions is minimal (i.e. $E_{Tx\_conn}$ is typically only 10% less than $E_{Tx\_disc}$). This results in the maximum energy savings being largely influenced by $n_{Tx\_max}$, as shown in (13).

$$\begin{aligned} E_{bit\_conn} &= n_{Tx\_min}(2E_{elec} + E_{TP\_conn}) \\ E_{bit\_disc} &= n_{Tx\_max}(2E_{elec} + E_{TP\_disc}) \\ E_{TP\_conn} &\approx E_{TP\_disc} \\ E_{disc\_max} &= \frac{n_{Tx\_max} - n_{Tx\_min}}{n_{Tx\_max}} \end{aligned} \tag{13}$$

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%.

## IV. Relationship between Channel Conditions and Energy Savings

As highlighted by Chandrakan et al. in [11], $E_{bit}$ consists of distance dependent and distance independent terms, $2E_{elec}$ and $\varepsilon_{amp}d^{\alpha}$ respectively. They concluded that for many short-range radios, the distance independent term typically dominates (i.e. $2E_{elec} > \varepsilon_{amp}d^{\alpha}$). To observe this characteristic, the dominance of the distance dependent term on $E_{bit}$ over varying communication distances and for different path loss exponents is presented in Figure 3.

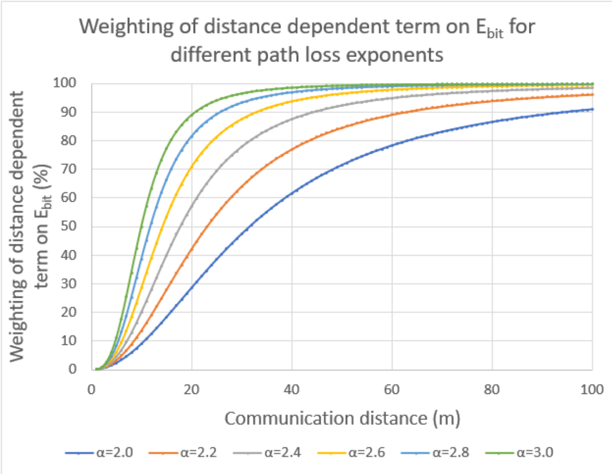


Figure 3, Weighting of distance dependent term on $E_{bit}$ for varying communication distance and path loss exponent.

As seen in Figure 3, 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 terms account for over 50% of $E_{bit}$) when the communication distance is greater than 30m. 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, in an office environment where α=3 [17], the distance dependent term becomes of significant influence when the communication distance is around 10m. 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, lower supply voltage, lower current consumption) would offer more opportunities as have been suggested in [8].

However, the HCB model calculates the nominal energy dissipated so its results are based upon using the nominal transmission power. To identify and maintain the optimum transmission power over time, a TPC protocol is required. Many current WSN standards (such as WirelessHART [14] and ZigBee [15]) use a fixed transmission power 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 transmission power at the maximum level, the distance dependent term will be fixed at its maximum value ($E_{max}$). The energy savings achievable through using the optimum transmission power, rather than the maximum, for different channel conditions (communication distances and path loss exponents) are shown by the green areas in Figure 4. Note the results in Figure 4 are based on the performance metrics of the Nordic nRF2401 [16] but other radio hardware will exhibit similar characteristics.

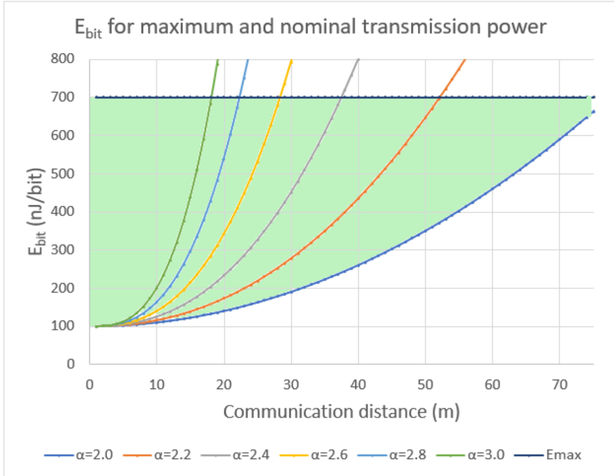


Figure 4, Potential energy savings through using the optimum transmission power.

Figure 4 shows that as the communication distance and path loss exponent increase, the potential energy savings are reduced. This highlights that the maximum energy savings can be achieved under ideal channel conditions and at short communication distances. This observation disproves previous assumptions about the limited impact of protocols and mechanisms that target the distance dependent term not offering significant energy savings at short communication distances.

## V. Conclusion

In this paper the potential energy savings achievable through the use of a TPC protocol have been quantified. The results show that optimising the transmission power 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 paper highlights that the energy consumed to transmit a bit of data can be reduced by up to 38-80% for links that belong to the connected region and up to 66% for links that belong to the disconnected region. Previous assumptions that protocols and mechanisms, such as TPC, that target the distance dependent term of $E_{bit}$ not being able to achieve significant energy savings at short communication distances have been disproven. This work has shown that the greatest energy savings are achievable at short communication distances and under ideal channel conditions.

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