On the Energy Savings of Adaptive Transmit Power for Wireless Sensor Networks Radio Transceivers

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Abstract

In this paper we present an adaptive transmit power optimization technique that is applied under varying channel to reduce the energy per successful transmitted bit. The output power is adaptively tuned to the best power level on link-by-link basis. Each node locally adapts the power according to the signal-to-noise ratio (SNR) variations (for all the neighbor nodes). The optimization is achieved under slow varying channel at the reception of a single packet. There exists an optimal point as the energy per bit reduces until a certain transmit power level and after that it starts increasing (as the signal power is too weak) due to retransmissions. These best points are identified under varying SNR conditions which provide some energy saving at the transmitter end. Different radio transceivers power profiles are used to show the gain over fixed transmit power. It is found that by dynamically adapting the transmit power on average can help to reduce the energy consumption by a factor of two.

1 INTRODUCTION

In wireless sensor networks (WSNs), tiny sensor nodes are equipped with limited battery and often are required to operate for a long time. Therefore the optimization of the power consumption of these devices is extremely vital. In typical WSN platforms, radio transceiver consumes major proportion of the energy [1]. In the context of radios transmit power optimization, connectivity between the nodes is a major concern. Transmit power can be reduced if the signal strength is better than environment noise. To ensure reliable and effective communications, a low transmit power can be adopted under good channel conditions, while a high power for bad channel conditions. In these regards, if the transmit power is too low then there are multiple disconnected clusters of nodes instead of a single well connected network. On the other hand, transmitting at excessively high power would lead to higher interference and a shorter battery life [4]. Therefore, to obtain a good connectivity, increased lifetime and reduced interference, the transmit power must be (just) high enough for a node to communicate successfully.

With regards to various radio transceivers, often there are multiple transmit power levels available that can be tuned to reduce power consumption [2], [3]. On the other hand, the static transmit power optimization can perform well if all the nodes are considered stationary and environment variations are assumed to be fixed. However, the second assumption is not practical because, even for static networks (for both indoor and outdoor deployments), there are some channel variations which can significantly degrade the performance of the communication if the transmit power is not selected to maximum level. Therefore, the power optimization can only be effective if the transmit power level is adapted dynamically according to channel variations.

In this context, an adaptive transmission power control technique is presented in this paper that is able to guarantee the successful transmission of data as well as to maintain near-to-optimal transmit power level for energy efficiency. The main idea behind the proposed approach is to adapt transmit power level according to the signal-to-noise (SNR) variations. After receiving a data packet and estimating the received SNR, the receive node calculates the energy per-bit (E_b) through bit-error-rate (BER) which is calculated against number of different transmit power values. The best transmit power is obtained through energy per successfully transmitted bit. The energy consumption is relatively higher for high power levels in comparison with the low levels and the optimal points are identified from a gradient of the curve. Different channel profiles are applied on different radio transceivers to evaluate the performance of the adaptive technique and further the results of energy consumption are computed for single packet transmission under low, medium and high SNR and the improvements are shown by a comparison of static transmit power optimization.

The rest of this paper is organized as follows. A state of the art is presented in Sec. 2 followed by the static transmit power optimization in Sec. 3. Then an adaptive transmit power control technique is proposed in Sec. 4 which is evaluated by the simulation results. The performance is analyzed by comparing the results of adaptive and fixed transmit power for different radio transceivers. Finally, a conclusion is presented.

2 Related Work

There are a number of distributed power control algorithms reported in the literature, some are designed with network connectivity and network longevity as their objectives such as proposed in [5], [7] and [9]. An algorithm proposed in [6] attempted to balance the power and delay

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trade-off by using local information such as last transmitted power level, last interference level at the transmitter to determine the appropriate power to transmit in the next time slot. [8] proposed a power management scheme for improving the end-to-end network throughput. However, most of these distributed power control algorithms were designed with the objective of ensuring network connectivity without considering any appropriate link quality estimation (LQE) metric.

Radio link quality estimation is a fundamental building block for wireless sensor networks, mainly for a reliable deployment, resource management and routing [10]. Generally link quality estimation can be estimated by utilizing built-in parameters of the radios such as received signal strength indicator (RSSI), link quality indicator (LQI), and signal-to-noise ratio (SNR). It has been found that by normalizing or averaging RSSI over a certain length helps to achieve better estimation instead of using an absolute RSSI value. The authors in [11] also have used multiple metrics (i.e., SNR, packet reception ratio (PRR) and LQI) for fast and accurate link quality estimation. [12] proposed similar technique and shows better improvements under variable link conditions. It is found that SNR-based approach or averaged RSSI/LQI based estimation can be a good consideration for the real-time implementation of our proposed technique.

We used SNR as a metric to characterize a link quality. [13] presents and interesting insight of link quality estimation under static network by using SNR metric. The computation of SNR is achieved by sampling the received signal strength indicator (RSSI) for every byte of data a node receives. Then, it averages these values over an entire packet length, it calculates an estimate of the average received signal power for a packet. By further sampling after the packet reception was complete, the receiver also obtains a value for the average noise power immediately after the packet.

3 Static Transmit Power Optimization for WSN

The power profile characteristics of different radio transceivers operating at 2.4GHz and 900MHz of spectrum (which are ISM bands widely used for WSN) are shown in Fig. 1. There are two important points related with the radio transceivers power profile. First, all the radio transceivers shown in Fig. 1 have only few possible transmit power levels which means that the adaptive transmit power optimization has to make a compromise by selecting one of these power levels and not the optimal power level as for example can be seen in Fig. 3. Second, most of the radio transceivers have flat power profile especially for lower power levels which results in a low gain in terms of adaptive transmit power optimization. It may be better for such transceivers to not operate at very low power level.

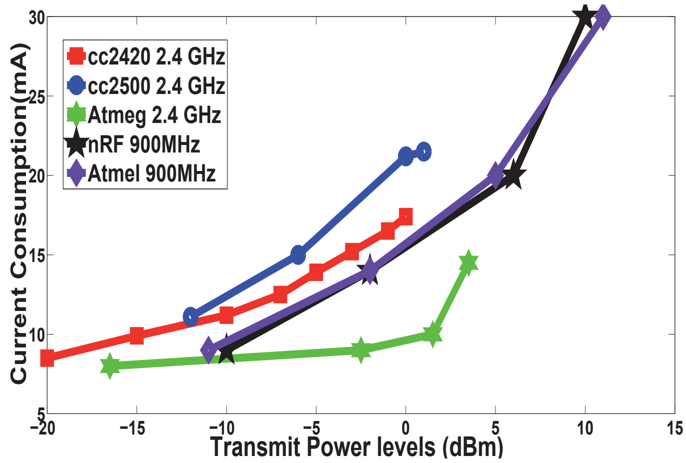

Figure 1: Power profile characteristics of different radio transceivers operating at 2.4GHz and 900MHz

In many wireless sensor networks applications, fixed transmission power is used for all the nodes without taking into considerations the variable distance between the nodes in the network and the channel variations. Fig. 2 shows the energy consumption per successful transmitted bit for fixed noise power with respect to different transmit power values. This curve is obtained through Matlab simulation. It uses an additive white Gaussian noise channel model with a channel attenuation coefficient γ equal to two, distance is considered fixed as ten meters, acceptable BER (bit-error-rate) is considered as 10^{-3} for a modulation scheme of BPSK and the energy per bit is estimated from

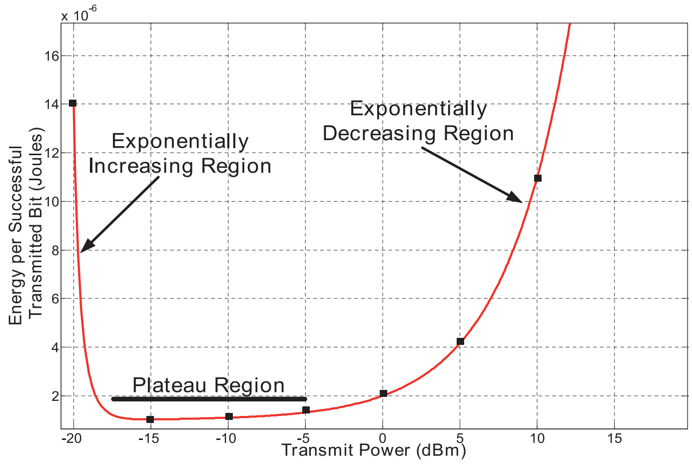

Figure 2: Energy consumption under fixed noise power against different transmit power

$$E_b = \frac{P_{tot}T_{tot}}{TX_{packets}pl} \quad (1)$$

where P_{tot} is the total power being consumed (including amplify power, digital and analog system power), and T_{tot} is the total time to transmit successfully all the pack-

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ets. $TX_{packets}$ and pl are the total number of packets to be transmitted and the packet length respectively. By decomposing the expression of T_{tot} based on number of automatic repeat request (ARQ) re-transmissions and using ARQ expression of packet-error-rate, the final expression for E_b becomes

$$E_b = \frac{P_{tot}}{R(1 - BER)^{pl}} \tag{2}$$

where R is transmission bit rate. During all simulations $TX_{packets}$ and pl are considered as 1000 packets and 16 bytes respectively as an example.

The curve (Fig. 2) shows three different regions, first as the power level starts reducing (from the maximum power level) the energy consumption reduces exponentially. In the second (plateau) region it can be seen that reducing the transmit power only has very minor reduction in energy consumption. Whereas, in the third region it can be seen that further reducing the transmit power results in an exponential increment of energy consumption. This is due to the fact of error detection and retransmission because of very low power level.

It is clear from the curve that the transmit power can be reduced instead of keeping it fixed at maximum power level. However, it is important to note that reducing the transmit power to very low level can result in degrading the energy efficiency due to re-transmission as most of the packets are lost or received with errors. Therefore, the best transmit power has to be carefully selected such that the energy consumption remains minimum even with slow channel variations. It is important for an adaptive transmit power optimization that there should be significant/meaningful difference between each power level of the radio chip. In these regards, we have considered two radio transceivers for further analysis one from each spectrum i.e. *cc-2420* for 2.4 GHz ISM band and *nRF-900* for sub-giga spectrum.

4 Adaptive Transmit Power Optimization

When looking at the static conditions which means fixed noise and distances between the nodes, it is evident that there exists a point on the curve which provides the minimum energy consumption against the best power level. In practice, it is not possible to have a fixed noise power and constant SNR therefore, often the transmit power is kept fixed to its maximum value which is not an optimized solution especially for limited battery operating devices.

Fig. 3 shows the energy per successful transmitted bit versus different transmit powers under varying noise power. Each curve represents different but fixed noise power on different curves and the optimal transmit power levels (in terms of energy) are obtained on each curve. It can be seen that for low noise power the transmit power can be reduced in order to optimize the energy consumption. Whereas, for high noise only higher values of the transmit power can be selected.

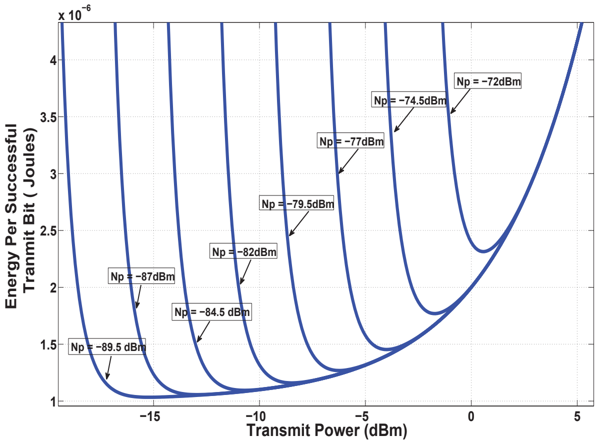

Figure 3: Energy consumption versus transmit power under varying but fixed noise power Np.

4.1 Algorithm

The algorithm to compute near-to-optimal transmit power level needs two important considerations. First, it has to be low in complexity such that the computation cost remains minimum and importantly the algorithm computation should be fast enough so that the transmit power can be tuned to the best level quickly. Second, it is important to assume a slow varying channel model because even if the best transmit power level is obtained through the transmission and reception of only one packet, it is only worth full if we consider the same channel conditions for at least 2 to 3 packets.

The computation of the adaptive transmit power algorithm consists of the following steps.

- As the data packet is received, the received power is calculated from the path losses and the known transmit power level of the transmitter that was updated by the receive node in the last communication. Further received SNR is calculated by assuming that the noise power is know at the receiver. This assumption is considered during simulation, however, in real life case noise power can be estimated through RSSI (as explained in [13]).

- After an SNR estimation, BER is computed by considering a minimum threshold of 10^{-3} (for BPSK modulation scheme) as acceptable error rate. After words, the energy per bit is calculated as explained in Sec. 3.

- For all E_b values against transmit power levels and corresponding possible SNR variations (under fixed noise at a time), there is always a transition point from where the energy per bit starts increasing.

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This transition point is considered as near-to-optimal point (as it is the minimum of transmit power versus energy consumption) and is identified through the sign of derivative which changes from negative to positive.

The receive node informs the transmit node (using an acknowledgment packet) about the optimal power level that the transmit node should use to transmit the next data packet under same channel conditions. It is important to mention here that in real-life implementation of above algorithm a look-up-table (LUT) can be used as an optimization to reduce the processing time. Such an optimization only requires SNR computation and after words a corresponding power-level can be selected.

4.2 Simulation Results

In this section, simulation results are presented by applying the adaptive transmit power technique under two channel profiles. We have considered an additive random noise channel profile to verify the performance of the adaptive algorithm. First, the randomness is selected according to different scenarios of obstacles such as slow and fast moving objects in the propagation path. Second, the variations are selected by knowing the fact that radio transmitter has a limit to maximum transmit power and if the noise power exceeds too high then the energy consumption will increase alarmingly. Therefore, we have considered two flat-fading slow-varying channel profiles which are shown in Fig. 4-a and Fig. 5-a (namely *model-a* and *model-b*) and are applied to *cc-2420* and *nRF-900* respectively. In both models it is assumed that the channel is stationary for the duration of at least 2 data packets, which is a minimum duration for adaptive transmit power to be useful. It to mention that the distance between the nodes is considered as fixed i.e. 10 meter during the entire simulations.

Fig. 4-b shows the energy consumption for three cases over a transmission period under channel variations from *model-a*. The three cases are fixed transmit power at 0dBm, adaptive (theoretical) transmit power and adaptive transmit power (at available power levels from *cc-2420* radio). It can be seen that the adaptive transmit power technique is always more energy efficient than fixed transmit power (as long as the channel noise is low) and it keeps the track of SNR variation very efficiently. Further, when the channel noise is maximum as it can be seen through several peaks (between 600 – 800s and 1600 – 1800s) in Fig. 4-b, there is no significant gain. Moreover, the adaptive transmit power is also tuned to the maximum power level under low SNR (that is energy efficient as low-power levels will results in more energy consumption due to retransmissions as explained in Sec. 3).

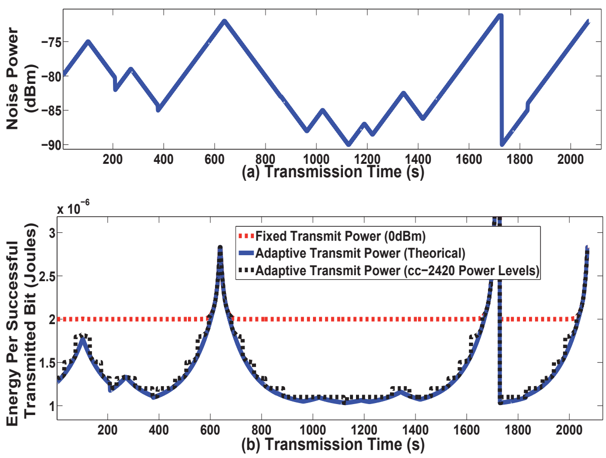

Figure 4: (a): Channel variations 'model-a'. (b): Performance of the adaptive transmit power technique against the channel variations of *model-a* over time

Fig. 5 shows the performance of the adaptive transmit power algorithm against the channel variations of *model-b* over time. The adaptive technique has a significant gain as the power profile of *nRF-900* has a higher slope which helps the adaptive technique to have a better gain over fixed transmit power. It is important to mention that radios operating at sub-giga spectrum usually can transmit the data for a longer distance but when such radio is used for short range transmission we have an average gain in the oder 5 to 8 times in comparison with a fixed transmit power.

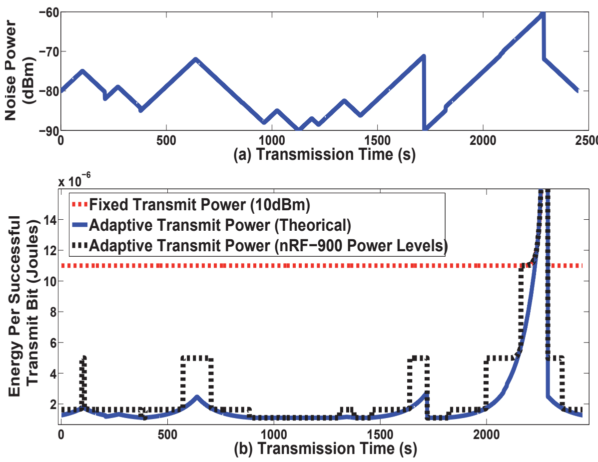

Figure 5: (a): Channel variations 'model-b'. (b): Performance of adaptive transmit power algorithm against the channel variations of *model-b* over time

4.3 Performance Evaluation

It is shown in previous section that an adaptive transmit power optimization technique can help to adapt the transmit power to the best possible level accordingly to the SNR variations. In order to show the improvements of adaptive transmit power optimizations effectively, it is important to

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make a quantitative comparison with the static transmit power. In this section the algorithmic proof-of-concept will be extended into performance evaluation results and a comparison with static transmit power consumption. In most of 802.15.4 communications, the transmit power is kept fixed to maximum power level. Therefore, 0dBm and 10dBm are the power levels selected from *cc-2420* and *nRF-900* transceivers respectively for the comparison.

Fig. 6 shows the performance of adaptive transmit power optimization versus fixed transmit power ($0\ dBm$). The *model-a* is applied to evaluate the energy consumption comparison by using *cc-2420* radio chip. It can be seen from Fig. 6 that under high and medium SNR values (i.e. for low noise levels), the adaptive transmit power technique is much more efficient and effective, whereas, under low SNR it is same as fixed transmit power. The overall average energy efficiency gain of adaptive transmit power is between 1.5 to 2 times.

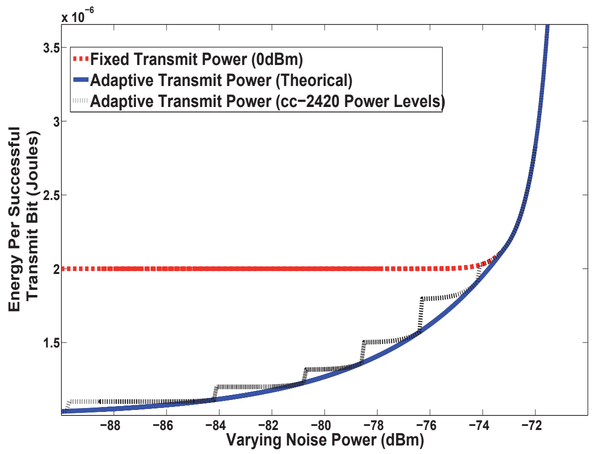

Figure 6: The comparison between an adaptive transmit power optimization versus the fixed transmit power at maximum level of *cc-2420* i.e. ($0\ dBm$)

Similarly, Fig. 7 shows the performance of adaptive transmit power optimization versus fixed transmit power (10dBm). The *model-b* is used for the comparison of *nRF-900*. It can be seen from Fig. 7 as well that under high and medium SNR values the adaptive transmit power technique is much more efficient and effective, whereas, under low SNR it is same as fixed transmit power level. The average gain is between 5 to 6 times, which is much higher in comparison with *cc-2420* because of the power profile characteristics which have significant (current) variations at different levels in comparison with *cc-2420*. On the other hand *nRF-900* transceiver has only four power levels and hence selecting one of these power levels minimizes the advantage of adaptive transmit power by compromising the near-to-optimal power level.

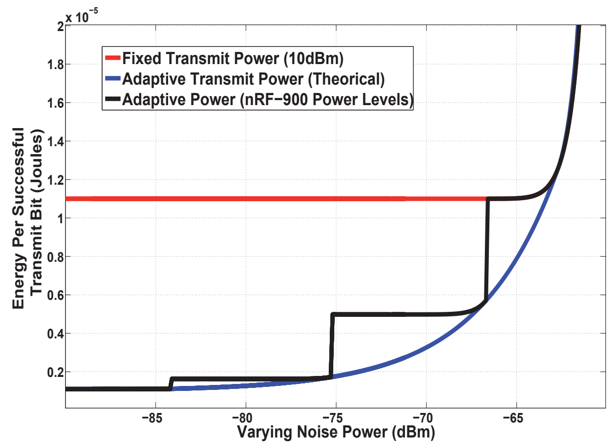

Figure 7: The comparison between an adaptive transmit power optimization versus the fixed transmit power at maximum level of *nRF-900* i.e. (10dBm)

Tab. 1 shows the energy consumption of different transmit power variants by using *cc-2420* radio transceiver under high, medium and low SNR which are obtained from *model-a*. It can be observed that the low SNR value matches in both cases because the best adaptive transmit power overlaps with the fixed transmit power at low SNR. The results shown in Tab. 1 are for a transmission of single data packet after the transmit node has already been tuned to the best power level. It can be seen that by using adaptive transmit power technique, the improvements on average are more than 30% which is a significant optimization for just the transmission of a single packet.

Tab. 2 shows the energy consumption of different transmit power variants by using *nRF-900* radio transceiver under high, medium and low SNR under *model-b*. Fixed transmit power at $10\ dBm$ is used to compare with the adaptive transmit power. Similar to Tab. 1, all the results and improvements have been shown for a transmission of one data packet in Tab. 2. It can be seen that by using adaptive transmit power technique for *nRF-900* radio transceiver the improvements on average is 86% which is better than that of *cc-2420*. The main reason of extra improvements are due to the fact that the power profile of *nRF-900* has higher slope in comparison with *cc-2420*.

5 Conclusion

In this paper an adaptive transmit power control technique is proposed with an objective to dynamically optimize the transmit power in WSN. The main idea behind the proposed approach is to adapt the transmit power according to the signal-to-noise (SNR) variations. In this regard, two random noisy channel models are used to evaluate the performance of the adaptive technique. Different radio transceivers were considered from 2.4GHz (*cc-2420* from TI) and 900MHz (*nRF-900* from Nordic Semiconductor) because of their different power profile character-

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Table 1: Performance evaluation of adaptive versus fixed transmit power under channel variations of *channel-a* for *cc-2420* radio transceiver

Transmit Power	High SNR (Joules/Packet)	Medium SNR (Joules/Packet)	Low SNR (Joules/Packet)
Max. Fixed (0 dBm) (Simulated)	$2.56.10^{-4}$	$2.60.10^{-4}$	$6.08.10^{-4}$
Adaptive (Simulated)	$1.32.10^{-4}$	$1.72.10^{-4}$	$6.08.10^{-4}$
Improvements(%)	49	34	0

Table 2: Performance evaluation of adaptive versus fixed transmit power under channel variations of *channel-b* for *nRF-900* radio transceiver

Transmit Power	High SNR (Joules/Packet)	Medium SNR (Joules/Packet)	Low SNR (Joules/Packet)
Max. Fixed (10 dBm) (Simulated)	$1.1.10^{-5}$	$1.1.10^{-5}$	$1.01.10^{-4}$
Adaptive (Simulated)	$1.1.10^{-6}$	$1.63.10^{-6}$	$1.01.10^{-4}$
Improvements(%)	90	86	0

istics. Further the results of energy consumption are computed for single packet transmission under low, medium and high SNR values. Finally the improvements are shown through a comparison of static transmit power with a dynamic power optimizations. It is shown that by adapting the transmit power according to channel variations can improve the energy efficiency by a factor of 2 to 5 times for different radios in comparison with worst-case static transmit power utilization.

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