Transmission power control techniques for wireless sensor networks

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Abstract

Communication is usually the most energy-consuming event in Wireless Sensor Networks (WSNs). One way to significantly reduce energy consumption is applying transmission power control (TPC) techniques to dynamically adjust the transmission power. This article presents two new TPC techniques for WSNs. The experimental evaluation compares the performance of the TCP techniques with B-MAC, the standard MAC protocol of the Mica 2 platform. These experiments take into account different distances among nodes, concurrent transmissions and node mobility. The new transmission power control techniques decrease energy consumption by up to 57% over B-MAC while maintaining the reliability of the channel. Under a low mobility scenario, the proposed protocols delivered up to 95% of the packets, showing that such methods are able to cope with node movement. We also show that the contention caused by higher transmission levels might be lower than analytical models suggest, due to the action of the capture effect.

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1. Introduction

Wireless sensor networks (WSNs) are a subclass of mobile ad hoc networks (MANETs), and consist of a large number of sensor nodes, composed of processor, memory, battery, sensor devices and transceiver. These nodes send the monitoring data to an access point (AP), which forwards them to the users [1]. Unlike traditional ad hoc networks,
in general, it is not possible to replace or recharge batteries due to the number of nodes deployed or inhospitable environmental conditions. Hence, energy conservation is a critical factor in WSNs.

Severe hardware and energy constraints preclude the use of protocols developed for MANETs, which comparatively possess more resources. The strict requirements of WSNs force networking protocols to be as much energy-efficient as possible. Medium access control (MAC) protocols, for example, modify transceiver parameters and the topology of the network in order to reduce energy consumption. One of the transceiver’s parameters is the transmission power.

Transmission Power Control (TPC) techniques improve the performance of the network in several aspects. First, power control techniques improve the reliability of a link. Upon detecting that link reliability is below a certain threshold, the MAC protocol increases the transmission power, improving the probability of successful data transmissions [2–5]. Second, only nodes which really must share the same space will contend to access the medium, decreasing the amount of collisions in the network. This enhances network utilization, lowers latency times and reduces the probability of hidden and exposed terminals [5]. Finally, by using a higher transmission power, the physical layer can use modulation and coding schemes with a higher bit/baud ratio [6,7], increasing the bandwidth in the presence of heavy workloads, or decreasing it to maximize energy savings.

Although being an effective mechanism to reduce energy consumption, TPC is not implemented in any existing MAC protocol for WSNs. This occurs due to the highly imprecise nature of readings provided by the transceiver, and also due to the restricted resources found in current nodes. Previous works are based on models and simulations that assume precise readings and that the transmission range can be assigned to an arbitrary value, which is not the case for real hardware. Our analysis, on the other hand, is based on experiments with production hardware employed by a number of research groups [8–11].

In this article we propose two transmission power control protocols for WSNs, which can be embedded into any existing MAC protocol. The first, called Hybrid, calculates the ideal transmission power using a closed control loop that iterates over the available transmissions powers in order to maintain a target link quality. The second, called AEWMA, employs calculations to determine the ideal transmission power based on the reception power, transmission power and average noise. Due to their simplicity, those protocols can also be applied to more resourceful networks. Experiments carried out in the Mica 2 platform showed the efficiency of the protocols, considering parameters such as energy and throughput. The experiments took place in indoor and outdoor environments.

This article is organized as follows. Section 2 summarizes the previous research on TPC techniques. The proposed methods are detailed in Section 3. The implementation of each techniques on the Mica 2 platform is discussed in Section 4. Section 5 describes the evaluated scenarios and presents the achieved results. Finally, Section 6 draws the conclusions and future work.

2. Related work

Gomez and Campbell analyzed the benefits of transmission power control in wireless multi-hop networks [2]. The authors showed that per-link range adjustments outperform global range transmission adjustments by 50%. Thus, instead of globally defining a transmission range that keeps the network connected, wireless networks should adjust transmission ranges on each link. They also demonstrated that the average traffic capacity per node is constant on a TPC-aware network even if more nodes are added to a fixed-size area. This is not true, however, if the transmission range is kept fixed. For such networks, the traffic capacity decreases when more nodes are added, due to increased interference.

Ammari and Das developed analytical models to evaluate how the transmission power affects latency and energy consumption in WSNs [12]. The authors showed that, by increasing the distance traveled at each hop, the end-to-end latency decreases at the cost of a higher energy consumption. For a small distance per hop, however, less energy is consumed, but the latency increases as more hops must be traversed. The authors then proposed the creation of quality of service (QoS) classes with different latency and energy guarantees based on the transmission power employed on the communication. The analytical models, however, do not consider the effects of collisions on the communication, a critical issue as the transmission power increases.

PCMA (Power Controlled Multiple Access) is a MAC protocol that allows communication at minimum propagation ranges, allowing spatial reuse of
The use of TPC techniques in the MAC layer alone is not sufficient, since the communication in MANETs is usually multi-hop. Thus, if the routing protocol does not take into account the differences of transmission power in each link, routes can be energy-inefficient. Based on this issue, Kawadia and Kumar studied in [16] whether TPC techniques should be implemented in the MAC or in the routing layer. According to the authors, TPC techniques should be coded in the routing layer in order to maintain modularity. Based on this assumption, they proposed four TPC-aware routing protocols to minimize the energy consumption in MANETs. In order to define the ideal transmission power for each link of the routes, the protocols execute several instances of a routing establishment algorithm, one for each transmission power available. Each instance periodically sends HELLO packets to identify the neighbors of the node, hence determining the nodes reachable by each transmission power. Packets are sent through the routes built with the smallest transmission power.

However, the protocols developed by Kawadia and Kumar spend a high amount of energy to build their routes due to the execution of several instances of the routing algorithm. As energy consumption is critical in WSNs, we advocate that the transmission power must be calculated by the MAC layer due to its higher energy-efficiency. TPC-aware routing algorithms would query the MAC protocol to check the transmission power or reliability of each available link.

A problem related to transmission power control is the propagation on low power wireless radios. Lal et al. characterized the reliability of wireless links and proposed algorithms to approximate it on real-time [17]. Reijers et al. [18] studied the effect of obstacles and environmental changes on link quality. Zhou et al. [19] developed a new propagation model that closely resembles the results obtained from experimental data. Son et al. studied the effects of concurrent transmissions on signal to noise ratio and on link reliability on WSNs [20]. They identified that collisions occur when the signal strength of two or more consecutive transmissions are separated by a certain threshold. For values outside this area, the weaker transmissions are ignored. De Couto et al. proposed an extension to Dynamic Source Routing (DSR), where the route calculation takes into account the reliability of the links, greatly reducing the amount of retransmissions [21]. Woo et al. proposed mechanisms to assess link reliability on WSNs.

The existing TPC methods for MANETs usually depend on calculations involving floating-point computations. Due to the severe hardware constraints of sensor nodes, the existing algorithms must be simplified or new algorithms tailored to restricted environments must be developed.

Lin et al. proposed a closed-loop TPC protocol for WSNs that approximates the ideal transmission power using linear equations [15]. Based on empirical data, the authors show that link quality can be roughly approximated by the received signal strength using a linear relation. This lead to the creation of a two-phase protocol. On the initialization phase, nodes send probe packets to all their neighbors, storing RSSI readings \( r_{ij} \) which is the received signal strength on node \( j \) for the \( t \)th iteration on transmission power \( t \) for all the available powers \( (p_t) \) on the radio. Using this information, the protocol finds \( a_j \) and \( b_j \) for every link \( j \) such that \( r_{ij} = a_j \times p_t + b_j \) using the least square approximation. On the operational phase, the protocol periodically sends probe packets to update both parameters. If the perceived link quality drops below a certain threshold, the receiver notifies the sender, which in turn recalculates \( a_j \) and \( b_j \) for the link.

Although computationally expensive, the authors argue that, as the noise level on the medium varies at most 3 dBm per hour, one might send one probe packet per hour to properly adjust the transmission power. The most significant drawback of the method is its enormous memory consumption, due to the huge amount of RSSI readings that must be cached to calculate the parameters of the curve. The authors show that, for 20 neighbors, their method consumed 50% of the total memory. Our method is much lighter, allowing the transmission power to be updated for every transmitted packet, and consumes only 10% of the available memory.¹

¹ A direct comparison is possible because both nodes use the same operating system and have the same amount of memory, differing only by the employed radio.
They model the reception of packets as a Bernoulli stochastic process and apply signal filters to determine the instantaneous packet reliability.

3. TPC techniques

In this section we describe the new TPC techniques. The first, called Hybrid, calculates the ideal transmission power using a closed control loop that iterates over the available transmissions powers in order to maintain a target link quality. The second, called AEWMA, employs calculations to determine the ideal transmission power based on the reception power, transmission power and average noise. These techniques can be deployed on any existing MAC, since they are simple enough to execute in restricted environments. In the following, the term “ideal transmission power” is defined as the lowest power level able to successfully transmit messages from a node to another.

3.1. The hybrid method

The ideal transmission power can be determined using successive refinements. Transceivers have a limited number of allowed transmission powers. In the Mica 2 platform, for instance, there are 22 different levels, separated by roughly 1 dBm [23]. Further, as the power switching operation is fast (it takes 20 μs on Mica 2 nodes), it is possible to iterate over the available power levels, increasing or decreasing the transmission power when necessary.

Algorithm shows the operation of the algorithm, which is described below. It operates in two phases, where the first phase (lines 8–14 of the algorithm) determines the ideal transmission power, while the second phase copes with medium changes. The algorithm works as follows. The first phase starts with the transmission power set to the maximum value allowed by the transceiver. A node wishing to determine the ideal transmission power sends a power query message ($M_{PQ}$) piggy-backed in data packets at the “current” ideal transmission power and waits for an acknowledgment (ACK) packet. If the reception is confirmed, the transmitter decreases the ideal transmission power by one level, and sends another $M_{PQ}$ message on the next data packet. When a $M_{PQ}$ message is not acknowledged (lines 22–28), the transmitter assumes that the ideal transmission power was found, triggering the second phase.

The second phase of the algorithm (lines 14–21 and 22–28) uses ACKs to adjust the transmission power.

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**Algorithm 1: The Hybrid method**

1: procedure \texttt{Hybrid}( )
2: \texttt{phase}_i ← \texttt{1st phase} \hspace{1em} ∀ i; //current phase for node \textit{i}
3: \texttt{received}_i ← 0 \hspace{1em} ∀ i; //no. of consecutive acks received
4: \texttt{lost}_i ← 0 \hspace{1em} ∀ i; //no. of consecutive packets timed out
5: \texttt{txPower}_i ← \texttt{maxTXPower} \hspace{1em} ∀ i; //Data packet received

\textbf{Require:} receive \hspace{2em} (data, src)
6: \texttt{ACK}.mustIncrease ← ($P_{RX} < \text{Noise} + \text{SNR}_{\text{threshold}}$); //packet sent to dst was ack’d
7: \texttt{send}(ACK, src, PRX); \\

\textbf{Require:} receive \hspace{2em} (ACK, dst)
8: \texttt{if} ACK.mustIncrease \texttt{then}
9: \texttt{received}_\texttt{dst} ← 0;
10: \texttt{lost}_\texttt{dst} ← 0;
11: \texttt{txPower}_\texttt{dst} ← \texttt{txPower}_\texttt{dst} + 1;
12: \texttt{else} \texttt{if} phase\texttt{dst} = 1\texttt{st phase} \texttt{then}
13: \texttt{txPower}_\texttt{dst} ← \texttt{txPower}_\texttt{dst} - 1;
14: \texttt{else}
15: \texttt{received}_\texttt{dst} ← \texttt{received}_\texttt{dst} + 1;
16: \texttt{lost}_\texttt{dst} ← 0;
17: \texttt{if} received\texttt{dst} = L_D \texttt{then}
18: \texttt{txPower}_\texttt{dst} ← \texttt{txPower}_\texttt{dst} - 1;
19: \texttt{received}_\texttt{dst} ← 0;
power as follows. If a number of consecutive transmissions are not acknowledged (this number is called the increase threshold level, or $L_I$), the ideal transmission power is increased by one level. Since the noise can also decrease due to environmental changes, communication can also improve, thus the transmission power is lowered if a certain number of consecutive messages are successfully received (the decrease threshold level, or $L_D$). The values of $L_I$ and $L_D$ must be set up according to the throughput of the application, avoiding a late reaction when the throughput is low and an early reaction when the throughput is high. The algorithm does not distinguish node and transmission failures due to the use of ACKs to assess link reliability. Broadcast packets are always transmitted at a fixed power since they are not acknowledged.

Initial experiments showed that the method presented fluctuations on the transmitted power [24]. Nodes used a transmission power too close to the average noise, thus reducing the probability of a correct reception. In order to avoid this, we apply Eq. (4) of the AEWMA method, shown in Section 3.2, to guarantee a transmission power that is always above the average noise by a certain threshold. Whenever a packet arrives at a reception power too close to the average noise, the receiver notifies the sender that the transmission power must be increased by one level (lines 6 and 7) using a special bit on the ACK. Upon the arrival of the ACK, the sender increases the transmission power by one level (lines 8–11). Due to the use of both iterative and mathematical techniques to assess the ideal transmission power, we call this method hybrid.

3.2. The AEWMA method

The second method takes into account that ideal transmission power can be calculated as a function of signal attenuation, and must satisfy the following conditions$^2$ [5]. The formulas refer to a sender, node A, and to a receiver, node B.

- The transmission power must lie within the operational limits of the transceiver:

$$P_{TXlower} \leq P_{TXmin} \leq P_{TXupper}. \quad (1)$$

- The transmission power must compensate the attenuation imposed by the propagation of the signal from the sender to the receiver, guaranteeing that the received signal strength is higher than the minimum sensitivity of the radio ($RX_{threshold}$). If the reception power is below $RX_{threshold}$, nodes will be unable to decode the message. The attenuation suffered by the signal ($G_{A \rightarrow B}$) is asymmetric, and is inferred by the transmitted ($P_{TX}$) and the received ($P_{RX}$) power:

$$G_{A \rightarrow B} = \frac{P_{RX}}{P_{TX}} \quad (2)$$

Thus, the ideal transmission power must satisfy the equation:

$$R_{TXmin} \geq \frac{RX_{threshold}}{G_{A \rightarrow B}} \quad (3)$$

- Another factor that influences the communication is the background noise (also referred as noise), caused by signals naturally present in the environment [17,18]. Thus, in order to differentiate data from noise, the reception power of the data must be higher than the power level of the noise ($N_B$) by a certain threshold, called $SNR_{threshold}$, as described in the following equation:

$$P_{TXmin} \geq \frac{SNR_{threshold} \times N_B}{G_{A \rightarrow B}} \quad (4)$$

$^2$ For clarity, the relations are expressed in mW.
In short, the ideal transmission power must satisfy Eqs. (3) and (4) at the same time, as expressed by the following equation:

$$P_{TXideal} = \max \left( \frac{R_{Xthreshold}}{G_{A\rightarrow B}}, \frac{SNR_{threshold} \times N_B}{G_{A\rightarrow B}} \right)$$

(5)

The AEWMA method uses Eq. (5) to calculate the ideal transmission power of the next transmission and works as follows. Nodes periodically sample the signal strength when no transmissions occur in order to determine the base noise ($N_B$). If node A wishes to communicate with node B, it transmits the first packet to B at the current transmission power ($P_{TX}$). The packet includes $P_{TX}$ on its headers. When B receives the packet, it determines the received signal strength ($P_{RX}$, or reception power) and calculates the ideal transmission power ($P_{TXideal}$) from A to B using Eq. (5). Next, B sends the calculated power to A piggy-backed on the acknowledgment. The received value is stored on a table to be used on subsequent communications with node B.

AEWMA assumes that the signal attenuation is symmetric. This is a reasonable assumption, since most MAC protocols in WSNs rely on some sort of acknowledgment messages, which requires reliable links on both directions. The values of $R_{Xthreshold}$ and $SNR_{threshold}$ vary for each transceiver, and thus must be empirically determined.

Initial testing showed that the output of the calculation fluctuates, since the input values are always changing due to small variations in the environment and the quality of the batteries [24]. The variation of the result in time is shown graphically in Fig. 1 by the dashed curve. In order to have a stable transmission power, we must apply signal filtering techniques to the result of Eq. (5) (the solid curve shows the filtered output). In order to do so, we employ an EWMA (Exponentially Weighted Moving-Average) function.

The EWMA function is a weighted average that assigns exponentially decreasing weights to old data. Suppose we take a sequence of readings ($I$) as input and output an instantaneous “average” for every new reading ($O$). This average is based on a factor $\alpha$, where $0 < \alpha < 1$. The output value in iteration $i$ is given by $O_i = O_{i-1} \times (1 - \alpha) + I_i \times \alpha$. The equation ensures that, in a given iteration $i$, the $(i-k)$th element of the input sequence will contribute with weight $\alpha \times (1 - \alpha)^{i-k}$ to the current output value. Another property of this calculation is that, by decreasing the value of $\alpha$, more importance is given to past inputs over the recent ones. The value of $\alpha$ must be carefully chosen, since a high value leads to constant variations on the output, while a low value leads to very slow changes. To avoid this effect on our experiments, Section 5.1 evaluates several values of $\alpha$, for both indoor and outdoor environments.

The choice of the averaging function took two factors into consideration. First, the memory footprint of the method should be as low as possible. Operations such as maximum, minimum, median and average were discarded, since the node must maintain a list of the last transmission power values for each link. Second, the implementation should be fast and simple, avoid floating-point variables, and using few or no divisions. Thus, functions relying on differential equations were discarded.

Although EWMA seems to require floating-point operations, by carefully choosing $\alpha$ values in the form $1 - \frac{1}{2^k}$, we were able to implement an integer version of the calculation using only three shifts and one addition. In fact, the EWMA function has been successfully used on WSNs to assess the link reliability on the standard Mica 2 routing protocol [10]. Further, the EWMA function is memory-efficient, as it stores only one variable, the current transmission power. Unlike the Hybrid method, where only the sender has to store state to implement the calculation, on EWMA both the receiver and the sender must store the transmission power.

3 Most embedded processors implement division on software, thus this operation should be avoided.
3.3. Complexity analysis

This section evaluates the memory and CPU requirements of the AEWMA method. The first constraint imposed on the TPC calculation is time-based. Since the ACK carries the calculated transmission power, the TPC algorithm must complete before the ACK is sent. In Mica 2 nodes, this time is equivalent to 600 µs.

Eq. (5) demands division operations, which require several cycles to complete. To make the implementation more efficient, we coded the operations using measures in dBm, thus requiring only additions and subtractions. We evaluated the running time of the calculation on an emulator of the Mica 2 processor to ensure that the method would not delay the transmissions [24]. After running 20,480 iterations of the AEWMA method, we found that the code compiled with no optimizations demands, on average 834.17 CPU cycles (208.54 µs), which is approximately the time required by the radio to transmit one byte. Hence, the AEWMA method uses one third of the maximum computational “budget”.

The choice of the filter function was based on both CPU and memory consumption. The Kalman filter [25] was discarded due to its high complexity as it demands matrix calculations. Thus, we were restricted to simpler filters, such as EWMA, PID and moving average.

Before implementing the filters in hardware, we tested them over a real trace of the transmission power calculation, in order to evaluate their effectiveness. We measured their performance based on their standard deviation for 400 runs. The threshold values of PID and the alpha value of EWMA were empirically varied in order to find their smallest standard deviation.

The moving average filter showed a high standard deviation, varying from 1.13 for the average of the last two packets up to 0.9 for the average of the last five packets. The EWMA, in contrast, decreased the standard deviation for increasing values of $\alpha$. For 0.5, for example, the deviation was equal to 1, decreasing to 0.85, 0.76 and 0.62 for $\alpha$ equal to 0.7, 0.8 and 0.9, respectively. Clearly, the EWMA function is a much better choice when compared to the moving average in terms of memory consumption, as it stores only the past output value and presents an adjustable standard deviation. The last filter tested was the PID filter, which obtained standard variations from the order of 0.85 up to 0.43. From this study we discarded the moving average filter due to their inferior result when compared to the EWMA and PID filters.

Next, we ran both EWMA and PID filters in an emulator for the Mica2 processor. First, in order to fit the algorithms in a sensor nodes, we made an implementation based only on integers to avoid floating-point emulation. A test on a PC using real traces showed that our implementation deviated at most 0.5 dBm from the result of their floating-point counter-part. Next, we ran the code on the emulator to identify their CPU consumption. As we could not inject traces into the emulator to provide realistic data, we ran the PID and EWMA algorithms 320,000 times. The EWMA demanded, on average, 20 instructions to complete, while the PID demanded 80. From this test we conclude that both PID and EWMA filters are suitable to WSNs. However, for simplicity reasons, we chose the EWMA over the PID because it demands only one parameter to be optimized, while the PID demands three.

4. Implementation of the TPC techniques

We implemented the TPC methods on the Mica 2 platform running the TinyOS operating system [26]. We chose this environment since the TinyOS and the Mica 2 architectures are de facto standards for commercial and academic WSNs. Furthermore, the hardware on Mica 2 represents the typical bandwidth, memory capacity and processor of other popular hardware choices.

The TPC techniques were implemented inside the standard MAC protocol provided in TinyOS, called B-MAC [8]. The B-MAC protocol is a CSMA/CA protocol without channel reservation (RTS/CTS messages). The use of acknowledgment (ACK) is optional, being defined by the application. The protocol does random back-offs to avoid collisions and keeps retransmitting packets until they are correctly received (when ACKs are activated).

Since the memory is a scarce resource in WSNs, we measured the amount of memory used by each method, including the underlying MAC protocol. B-MAC took up 241 bytes (out of 4KB), the Hybrid method required 353 bytes and the AEWMA method required 393 bytes, respectively. Most of the increase in memory consumption was due to

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4 Assuming the typical bandwidth on Mica 2, which is 38.4 kbps.
the neighbor table that stores the information required to calculate the transmission power for each node. This table is composed of 20 entries, allowing each node to communicate with 20 of their neighbors at a time. The table size is fixed due to limitations of the language used to program the nodes, which does not allow dynamic memory allocation. Since the number of nodes on the table is modifiable at compile time, WSN designers can adjust its value according to the needs of each network. Although each entry requires 4 bytes for the most memory-hungry method, the transmission power table accounted for an increase of RAM usage of 63%.

Because the transmission of data spends more energy than the computation, we opted to minimize the number of bytes transmitted in detriment of memory and processing efficiency. Thus, power control information is piggy-backed in data and acknowledgment (ACK) packets. The additional headers increased the data packet size by three bytes (one byte for the transmitted power and two bytes for the sender address). ACK packets are increased by five bytes (two bytes for the sender address, another two bytes for the receiver address and one byte for the ideal transmission power).

The parameters of each method were defined after a series of experiments (see [24] for more details). We determined the SNR threshold as 10 dBm and RX threshold as $-85$ dBm. For the Hybrid method, $L_I$ was set to one and $L_D$ to eight.

The evaluation of $\alpha$ is shown in Section 5.1.

5. Evaluation

This section evaluates the implementation of the proposed TPC techniques on the Mica 2 platform. We evaluate two metrics, the average transmission power and the average delivery rate. Their values are taken from the mean of five independent experiments with a confidence interval of 95%. The proposed TPC methods are compared against the unmodified B-MAC protocol running at 5 dBm and at 0 dBm. We chose the first value since it is the highest transmission power of the radio, and thus must yield the best communication in terms of link quality and number of packets delivered. We chose the second value (0 dBm) because it is the default power of the radio, thus being used in most applications. Results were not taken for other values due to the time-consuming nature of the experiments.

5.1. Alpha in EWMA

Since the performance of the AEWMA method is heavily dependent on the selection of $\alpha$, we performed a set of experiments on indoor and outdoor environments to evaluate the most suitable value for each environment. In order to speed up the computation, we showed in Section 3.2 that the value of $\alpha$ must be in the form of $1 - \frac{1}{C_0^2}$. We used the values 0.03125, 0.125, 0.25 and 0.5. Note that higher values of $\alpha$ will increase the variation of the signal, as the most recent measurements have a higher weight on the calculation. On the other hand, when $\alpha$ is too small, the time required to converge is high and the output takes a long time to react to changes. Due to those considerations, we do not employ values over 0.5 or lower than 0.03.

Outdoor scenario: In this scenario we evaluate four different values of alpha for distances among nodes varying from 5 up to 20 on increments of 5 m. Results are averaged over four independent experiments with a confidence interval of 95%. In terms of average delivery rate, most configurations performed similarly, delivering as much as 97% of the packets. For an $\alpha = 0.031$, however, the delivery rate was up to 3% smaller than the others due to the long time necessary to respond to changes in the transmission power. The average transmission power is shown in Fig. 2. The conservative value of 0.031 performed poorly, employing 5 dBm. We attribute this to the long convergence time of the estimator, making it more conservative. For a high value of $\alpha$, such as 0.5, the filter gives too much importance to the recent calculation, thus incorporating spikes in the transmission power. Those vari-

![Fig. 2. Average transmission power for some values of $\alpha$ in an outdoor scenario.](image-url)
lations make the output signal stronger. The delivery rate and transmission power analysis suggest that the best values for \( a \) at an outdoor environment are 0.125 and 0.25, because they allow a high delivery rate at a reduced transmission power.

**Indoor scenario:** In this scenario we put the nodes on the floor of an empty corridor. We performed measurements for distances of 2.5 m, 5 m, 7.5 m and 10 m, because the range was lowered due to the smaller height when compared to the outdoor environment. Again, all protocols obtained similar delivery rates, correctly transmitting more than 95% of the packets in all configurations. As Fig. 3 shows, the protocols also had very similar transmission powers, probably due to a mild environment. This assumption is corroborated by the confidence interval, which was always smaller than 2 dBm in the indoor environment, while in the outdoor environment it reached ±4 dBm for certain configurations. Thus, for this particular scenario, the choice of \( a \) did not influence the performance significantly.

### 5.2. Outdoor environments

The outdoor experiments were performed in an open field, avoiding thus any source of interference. Two Mica 2 nodes, one receiver and one transmitter, were separated from 5 up to 20 m of each other, and placed 71 cm above the ground. The sender node transmitted 4 packets per second, for a total of 1000 packets. The AEWMA protocol was evaluated taking into account two values of \( a \), 0.25 and 0.125.

The average delivery rate is shown in Fig. 4. B-MAC at 5 dBm keeps an astounding 97% of packet delivery for distances of 5 up to 15 m. For 20 m, however, its performance declined to 75% B-MAC was closely followed by the AEWMA protocol, which delivered more than 93% of the packets for all distances from 5 to 10 m. For the distance of 20 m the AEWMA protocol outperformed all the other evaluated protocols, achieving 86% of delivery rate. In this scenario, the AEWMA method using \( a = 0.125 \) surpassed the AEWMA method using \( a = 0.25 \). The Hybrid method delivered up to 96% of the packets for distances from 5 to 10 m. The graph shows that the proposed protocols achieve delivery rates similar to the ones achieved using the maximum transmission power of the radio.

The transmission power for all protocols is shown in Fig. 5. This metric portrays the advantage of using TPC, since the most important advantage of such techniques is their energy savings. The first issue to be noticed is that the transmission power for the proposed TPC methods is fairly similar. The Hybrid method showed slightly higher transmission powers, but it was more stable, as the confidence intervals show. For distances equal to
or larger than 15 m, all TPC protocols employed a transmission power over 0 dBm. Hence, the poor performance of B-MAC using 0 dBm in Fig. 4 corresponds to the use of an insufficient transmission power. For transmission powers of 15 m and 20 m, the TPC techniques had to transmit at around 3 and 5 dBm, thus B-MAC at 0 dBm should have an insignificant delivery rate.

Converting the achieved transmission power to the energy consumed by the radio, we found that the AEWMA method consumed 57.5% and 43% less than B-MAC in 5 m and 10 m, respectively, for a transmission power of 5 dBm. Comparing to B-MAC at 0 dBm, the AEWMA method consumed 35% and 13.5% less for the same distances. The Hybrid method consumed up to 13% more energy than the AEWMA method, since it was more conservative when decreasing the transmission power. Overall, AEWMA slightly outperformed the Hybrid method. All TPC methods delivered as much packets as B-MAC and consumed less energy for 5 and 10 m.

5.3. Indoor environments

In this scenario, a sender transmits 1440 packets during a period of 6 min. The receiver node was 3.9 m apart from the sender, in a computer lab with people moving around. This test aims to identify how protocols behave in an indoor environment with various obstacles and sources of interference.

The first set of experiments evaluates the best values for the parameters of each protocol. We varied the values of $L_I$ (number of consecutive packets not acknowledged to increase the transmission power) for the Hybrid protocol, and $\alpha$ for the AEWMA protocol. In contrast to the outdoor environment, in the indoor environment the likelihood of two packet failures in a row is slightly higher. Hence, when increasing $L_I$ from one to two, we were able to achieve the delivery rate found in the outdoor scenario (95%). The average transmission power when $L_I = 2$ is around 16% smaller when $L_I = 1$, $(3.7 \pm 0.55)$ dBm and $(4.3 \pm 0.65)$ dBm, respectively. For the AEWMA protocol, as shown in Section 5.1, the value of $\alpha$ on the indoor environment makes almost no difference to its performance due to the mild environment.

The last protocol evaluated was B-MAC, transmitting at 5 dBm. Since it used a higher transmission power than the TPC protocols, B-MAC achieved a delivery rate of 97.9%, which is around 2% superior to the best results achieved with transmission power control, though at the cost of a higher transmission power.

5.4. Spatial reuse

The next experiment evaluates medium reuse and interference. We positioned four nodes in line directly on the ground in an empty corridor, as depicted in Fig. 6 (arrows denote data transmission). The nodes were deployed very close to each other because the transmission range is significantly lowered when nodes are placed on the ground. Nodes transmit at a rate of 12.5 packets per second, which is the maximum rate at which nodes are able to log the packets for later analysis. This is a limitation of the OS, as the effective bandwidth utilization of 12.5 pps is far from the maximum supported by the radio.

In order to justify this scenario, we recur to a simple queuing theory model to identify the probability of finding a busy medium. The radio transmits 38,400 bps in manchester encoding, and a packet is composed of 46 bytes, including the preamble, synchronization bytes and data. Assuming that packets are produced at a rate of 25 pps (the aggregate throughput of both transmitting nodes), the probability of a node finding at least one client on the system, which is equivalent to having someone already transmitting, is equal to 23.95%.

The aim of this scenario is to measure the contention on the medium, as well as the amount of collisions. We use those metrics to verify whether the use of transmission power control allows more concurrent transmissions at the same time, as indicated by previous analytic results [2]. According to those
results, a reduced transmission power decreases the amount of nodes that compete for the medium.

Fig. 7 shows the probabilities of packet loss and of the node finding a busy medium for each protocol, and the transmission power. Clearly, the transmission power influences the number of times that the medium was found busy, as we can see by comparing B-MAC using 5 and 0 dBm. For this node configuration, B-MAC at 5 dBm has a 10% chance of rescheduling the transmission for a later time due to an ongoing transmission from other node. When B-MAC transmits at 0 dBm, the probability of a busy medium is lowered to 5%. For the AEWMA and Hybrid TPC methods, the probability of a back-off is lowered to 3.9% and 2.3%, respectively. Hence, a lower transmission power decreases the probability of back-offs, improving the throughput and delay of the network.

When comparing the amount of back-offs with the queuing model above, we clearly identify that the amount of collisions observed is much smaller than the predicted value. This is due to the capture effect, which was previously reported in the Mica 2 nodes [8,27], and occurs when a node receives two transmissions at the same time with very different transmission powers. In this situation, the receiver correctly decodes the stronger signal, ignoring the lower signal. Hence, collisions occur only when the reception power of the two packets differ slightly. Next, we checked the amount of packets lost. We empirically found that the amount of packets lost for all protocols in this scenario is identical to the amount of packets lost without concurrent transmissions, when compared to the results of scenario 5.3 (indoor), suggesting that the TPC techniques do not reduce packet losses.

5.5. Multi-hop transmissions

In this scenario we placed five nodes in a row, simulating a multi-hop path. This experiment tests how TPC protocols behave with concurrent transmissions and how errors propagate in a multi-hop path. A node in position $i$ on the row receives a message from the node in position $i-1$ and forwards it to the node in position $i+1$. This process is repeated until the end of the line is reached. We used a static hard-coded route, to avoid routing exchange messages. This experiment was performed outdoors, in an area free of obstacles, with nodes 71 cm above the ground distanced 5 m from each other. The first node on the line sends packets at a rate of 4 pps.

Fig. 8 shows the results. For this particular setup, we observe that protocols employing a fixed transmission power consume more energy than the TPC enabled protocols. The Hybrid protocol showed the best results, transmitting data on $-16$ up to $-13$ dBm. In general, the performance of the AEWMA and Hybrid methods was very similar, due to the small distance among nodes. The transmission power on each link was slightly different, mostly due to node and antenna positioning, but also due to differences in each sensor node. The delivery rate for all protocols (not shown) was around 98%, as expected in such short distances.

The nodes in the middle of the line, which are the most requested (as they compete with the previous and the next hop to transmit and receive their data), suffered no performance losses when compared to our two-node setups. As the delivery rate of all nodes was statistically the same, the existence of concurrent transmissions on this scenario did not degrade the performance of the network.

![Fig. 8. Average transmission power in the multi-hop experiment.](image-url)
5.6. Node mobility

Our last experiment evaluates how protocols behave on mobile scenarios. We used two nodes, where one of them is fixed. The mobile node moves at a uniform speed of 0.5 m/s, and varies its distance in relation to the fixed node. The distance is varied from 1 m up to 15 m, and the experiment was performed on both indoor and outdoor environments. We do not vary node speed due to limitations in our experimental setup. Results are averaged over the experiments and shown with their respective standard deviation.

Figs. 9 and 10 show the average delivery rates in an outdoor and in an indoor environment, respectively. We show the results when nodes move away from each other (Distancing curve) and when they move closer to each other (Approaching curve). The third curve comprises the results of the two movements analyzed together. To our surprise, both AEWMA and Hybrid methods showed packet losses around 5% in the outdoor experiment, which is very similar to the rates found with static nodes. Although we saw no variations in delivery rates in this particular setup, we believe that higher speeds will impact packet losses, as both methods need a certain time to respond to variations. Hence, we plan to evaluate higher speeds in a future experiment.

For the indoor scenario, however, all protocols showed lower delivery rates. The difference among B-MAC and the TPC protocols increased from a few percents to around 10–20% for the AEWMA and Hybrid methods, respectively. Also, the difference at the average delivery rate when the mobile node moves towards the static node is higher than when it moves away for the indoor environment. Hence, TPC protocols must respond faster to movement, using more frequent probing, or increasing its signal-to-noise threshold (SNR_{threshold}).

Fig. 11 shows the transmission power for an outdoor environment, and Fig. 12 shows the results for an indoor environment. In these figures we plot the transmission power for each second of the experiment, in a trajectory where nodes first move away and, after the period delimited by the dashed line, move towards a stationary node. The AEWMA method sent packets with a lower transmission power than the Hybrid method, however its variation was more pronounced. Unlike the AEWMA method, the Hybrid method behaves differently when a node is approaching or distancing from the receiver. This occurs due to the high value of $L_D$ (set to 8) when compared to $L_I$ (set to 2), hence the protocol decreases the transmission power slowly, meanwhile it increases the transmission power swiftly. Hence, the parameter values employed in this experiment, which are the default values in a static deployment, are not suitable to mobility scenarios. In contrast to the outdoor environment, the transmission power in the indoor environment is more unpredictable, as seen by a higher value in the standard deviation. In this scenario, however,
the differences among the TPC methods are less pronounced.

6. Conclusions and future work

Wireless sensor networks must be designed with energy-efficiency in mind. The adjustment of the transmission power, performed by transmission power control (TPC) protocols, is a technique to diminish energy consumption in the communication. Due to the limited resources of wireless sensor networks (WSNs), the TPC techniques proposed for mobile ad hoc networks (MANETs) are not applicable to WSNs. This article introduced and evaluated through experiments two new TPC techniques specifically designed to WSNs.

The protocols were evaluated in diverse scenarios, varying parameters such as the environment type, the distance among nodes, multi-hop transmissions and mobility. Results showed that our enhancements enabled energy savings of up to 57% over fixed transmission power communications. Further, our evaluation showed that TPC techniques increase the throughput due to an increased spatial reuse, as a lower transmission power diminished the amount of back-offs before nodes send their packets. We found that the amount of packet drops also depends on the capture effect, which is not considered on existing analytical models. Finally, TPC protocols must be adjusted to accommodate mobile nodes, since in such situations their parameters must be tuned to provide a faster response.

TPC techniques can achieve higher gains when tightly integrated with communication protocols. Routing protocols, for example, could be modified to use the transmission power as a routing metric, thus defining energy-savvy routes. TPC techniques must also be extended to support broadcast and multicast packets. We plan to study both problems in future works.

References


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