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Research Article

Link Quality-Based Transmission Power Adaptation for Reduction of Energy Consumption and Interference

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Today, many wireless devices are mobile and battery powered. Based on the fact that battery capacity is still limited, energy saving is an important issue in wireless communication. Meanwhile, the number of wireless devices continues to increase and this creates interference problems between wireless devices. In this paper, we look at transmission power control and propose a mechanism that tries to achieve minimum energy consumption or emission under any circumstance. Lower transmission power levels may result in more retransmissions, but in total, energy consumption or emission still can be reduced in many scenarios. To evaluate the performance of our mechanism, we used real wireless channels in an indoor environment to carry out measurements. The measurement results indicate that a significant amount of energy consumption or emission reduction can be achieved for the transmitter in most scenarios compared to using a fixed transmission power level for all packets.

1. Introduction

Plenty of wireless devices use battery-based power, but the battery technology does not keep up. To increase device service duration, saving power is crucial. Power saving in communication can be achieved by different methods at different communication layers. Power-aware routing selects routes that together consume less energy or use devices that have more energy [1]. In the MAC layer, the receiver can turn off the receiver function periodically to save energy [2]. Another way of saving energy is to adapt the transmission power for the transmission of packets. Power transmission adaptation can achieve two benefits: save energy and reduce interference. Interference is becoming an increasing problem due to the enormously growing number of wireless devices. One way to alleviate this problem is to reduce the emitted transmission power.

The motivation for transmission power adaptation for energy saving and interference reduction stems from the fact that many of the current wireless communication systems (e.g., IEEE 802.11 and IEEE 802.15.4) usually use a fixed default transmission power level for all transmissions. However, when two nodes are very close to each other, the default power level is much higher than required to successfully deliver all packets. This both wastes energy and creates unnecessary interference. A lower transmission power level may require a larger number of retransmissions, but overall less energy will be emitted or consumed for each transmission and in total, there may be less waste. Therefore, a trade-off is possible between the number of retransmissions and energy consumption for each packet delivery. This trade-off requires the knowledge of the packet delivery ratio (PDR) for each transmission power level. We call this the *PDR-table*. The PDR-table differs between different links and different environments. To always select the transmission power level that consumes the least energy or have lowest energy emission, a self-adaptive transmission power adaptation mechanism is required that accurately observes the PDRs. In this work, we focus on IEEE 802.11 and IEEE 802.15.4 as our experiment technology. However, our methods can be used in other radio technologies as well.

Energy consumption for IEEE 802.11 is not so crucial as for IEEE 802.15.4, since IEEE 802.11 is normally used with larger devices, such as laptops, PDAs, and mobile phones, which can be recharged easily. However, minimizing energy emission is still important because of the interference.

For IEEE 802.15.4, energy consumption is critical due to its use in wireless sensor networks. Therefore, we mainly discuss interference reduction for IEEE 802.11 and energy saving for IEEE 802.15.4.

In this paper, we propose a power transmission control mechanism that is based on gathering PDRs for every transmission power level (the PDR-table). It consists of two phases: *initialization* and *updating*. It can be used both as an interference reducing mechanism and an energy saving mechanism depending on the energy model. We propose five different methods for the initialization phase. In the updating phase, we use an exponential weighted moving average (EWMA) method to update the PDR for each transmission power level and use the result to select the optimal level. To the best of our knowledge, we are the first to select the transmission power that achieves the minimum energy consumption or emission for delivering a certain amount of information based on link PDR-tables. We explore the maximum potential reduction of energy emission and consumption by an investigation of all relevant parameter combinations in our mechanism. The proposed mechanism is evaluated based on measurement data and the results indicate that significant savings can be achieved in many scenarios compared to always using the default transmission power level. We also compare our PDR-based mechanism with one that uses signal strength. Also there, the results indicate a significant improvement.

The rest of this paper is organized as follow: Section 2 introduces related work and Section 3 presents our measurement results and shows the potential reduction of energy consumption and emission. Our PDR-based transmission power adaptation mechanism is introduced in Section 4. In Section 5, our experimental system is described and in Section 6, the measurement results are presented. The paper is concluded in Section 7.

2. Related Work

Transmission power control requires good knowledge of the correlation between link quality and transmission power levels. This correlation has been studied before via measurement activities. In [3, 4], the correlation of transmit power level and packet delivery probability was analyzed in different indoor scenarios. Based on their observations, small adaptations in the power level do not change the packet delivery ratio in any measurable way. Some work also discussed combinations of power and rate adaptation to achieve good performance. In [5], it was proposed to select data rate and transmission power based on link quality. The method was applied in an indoor environment and achieved higher throughput than the traditional mechanism. However, energy consumption was not calculated.

Most previous work on applying transmission power adaptation schemes was more focused on reducing interference, maintain connectivity, and topology control, such as [6–9]. Paper [10] discusses the use of transmission power control to select reliable links and disable unreliable links via a blacklisting method in order to improve the system performance. Paper [11] discusses the use of transmission power control to reduce interference and simulation results reveal that throughput can be increased by adapting the transmission power in an ad hoc network. This shows the benefit of reducing energy emission. However, the aim of these papers were to maintain the link quality at a certain level, control the topology, and increase throughput by using transmission power adaptation. Energy was not their main focus and the selected transmission power level does not always result in the minimum energy consumption or emission level.

A few papers address energy saving explicitly. The authors of [12] proposed to use a RTS-CTS handshake in the highest power level to discover the channel quality and then use the lowest possible power level for the data packet. Simulation results show that the proposed power mechanisms can achieve energy savings without degrading the throughput. However, in their proposal, a separate channel is used for controlling, which means that adaptations to the IEEE 802.11 standard are necessary. Meanwhile, a theoretical model does not reflect the real channel situation accurately. In [13], a loop-based mechanism is used to adapt the transmission power level to achieve the minimum required power level for message delivering. Simulation results show that energy can be saved and throughput can be increased. However, this work also assumes that a RTS-CTS handshake is used. Moreover, a mechanism that adapts the transmission power level one level at the time will be too slow for fast channel variances. It may take several periods for the system to choose the appropriate power level.

In [14], the authors propose a power saving algorithm that adjusts the transmission power and extends the network lifetime. Again, only simulations are used to validate the proposed protocol. Paper [15] is the most similar work to ours; transmission power adaptation was used for power saving in different scenarios. However, the optimal transmission power level is set by the received signal strength. We use PDR information for two reasons. First of all, the mapping between PDR and received signal strength is not straight forward and noise and interference have a large impact on the mapping. Second, different receivers have different sensitivity levels and using received signal strength may require different thresholds for different devices. A PDR-table method is affected by different devices. We compare this mechanism with our mechanism in Section 6.

3. Energy Emission and Consumption Measurements

To minimize the energy consumption or emission for successfully delivering a fixed amount of information, such as a certain number of packets, we turn to the expected energy consumption or emission. We calculate the expected total energy consumption or emission for one packet delivery as follows:

$$E = P \cdot N \cdot T, \quad (1)$$

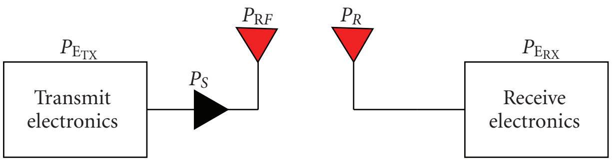


Figure 1: The high level block model of an RF link.

where E is the total energy consumption or emission for successfully delivering one packet (in Joules). P is either the energy emission or the energy consumption (in Watt), N is the expected required number of transmissions to successfully deliver a packet (i.e., $N = 1/\text{PDR}$), and T is the duration (in seconds) for one packet transmission including headers and preambles. We can see that if we use a single data rate and packet-size, T will be a constant value. E can be calculated for each transmission power level and the result can be used to find the optimal level, that is, the one with the lowest E. Depending on what P value we use, we will optimize for different things. For instance, if we are interested in minimizing energy emission we use the following formula:

$$P = P_{RF}, \tag{2}$$

where P_{RF} is the energy emission created by the transmission power level. For IEEE 802.11, the transmission power range is from 0 to 15 dBm and for IEEE 802.15.4, it is from −25 to 0 dBm [16]. Our 802.15.4 device has 31 different power levels, but we used only 15 of them, which we calculate in this simplified way: level 3 corresponds to −23 dBm and level 31 corresponds to 0 dBm and then we assume a linear correlation to map the transmission power levels in between to the different energy emission levels in dBm.

For minimizing the energy consumption, we also need to consider the energy consumption of the wireless device circuit, the energy consumption ($P_{E_{TX}}$) of other parts, and the wireless card amplifier energy consumption (P_S) as shown in Figure 1. While P_S is dependent on the transmission power level, $P_{E_{TX}}$ is not.

For calculating the total energy consumption, we refer to the results in [17, Figure 5]. Since measuring the PDR introduces a lot of inaccuracies, we do not need a perfect approximation of the energy consumption. Hence, we can simply use the following linear equations for approximating the energy consumption:

$$P = 10 \cdot P_{RF} + 1400; \quad \text{(for IEEE 802.11)}, \tag{3}$$

$$P = 35 \cdot P_{RF} + 30; \quad \text{(for IEEE 802.15.4)}. \tag{4}$$

If we only calculate the energy emission to the environment, (1) and (2) are used. If we calculate the total energy consumption of the whole transmitter, (1) and either (3) or (4) are used.

To capture the accurate correlation between transmission power and PDR, a measurement-based method has to be used. For this reason, we carried out measurements in an indoor environment with different radios and configurations. For all experiments, the same number of packets (2000) were sent with 15 different transmission power levels. Two different radio technologies were used, IEEE 802.11 and IEEE 802.15.4. Let us first start with IEEE 802.11. We used UDP with a fixed packet-size of 1500 Bytes including the IP header due to the fact that this packet-size is common in the Internet traffic [18]. We ran some indoor scenarios with different locations, but with a fixed data rate. Then we tried different data rates in the same location. The results are presented in Figure 2. The first group of experiments were done with 2 Mbps data rate in three different scenarios, using different distances between the sender and the receiver. The measurement PDR-table of the three stationary scenarios is plotted in Figure 2(a). The second group of experiments were done with different data rates and are presented in Figure 2(b). All scenarios and the experiment setup details are further described in Section 5.

At the receiver side, we recorded the PDR for each transmission power level. When doing this for our scenarios, we obtained the results in Figures 2(c) and 2(e). We can see that a certain transmit power level achieves the minimum energy emission or consumption and they are different for different links. The minimum energy emission level for each link in Figure 2(c) is 3, 6 and 9 for each link, respectively. For the energy consumption, we use log scale to show the results due to the large differences. We can still see that there is a level which results in the lowest energy consumption for the transmitter, and this level is not the highest power level.

To show that this phenomenon not only exists for IEEE 802.11 with 2 Mbps data rate, we carried out measurements for many data rates. The power trade-off for IEEE 802.11 with different rates is presented in Figures 2(d) and 2(f). It is interesting to see that for higher data rates, for example, 54 Mbps, the level that results in minimum energy consumption and emission is 15. This is caused by the fact that the link quality is so poor and struggles even with full power.

In Figure 3(a), the PDR-table with different transmission power levels but with a fixed packet-size in IEEE 802.15.4 is presented. We can see that although the power level is different from IEEE 802.11, the results are similar to Figure 2(a). For IEEE 802.15.4, only one data rate is possible, but we can change the packet-size. When we change the packet-size in Figure 3(b), we can see some PDR changes. However, the PDR difference is not very obvious. We also calculated the expected energy emission and consumption for IEEE 802.15.4 and present the results in Figures 3(c) and 3(e). The power trade-off for IEEE 802.15.4 with different packet-sizes is presented in Figures 3(d) and 3(f). The expected energy emission and consumption are calculated and compared with the case where we assume that every link had to deliver the same amount of bytes. We used 100 Byte as assumed payload, which means for a 20 Byte packet payload, one needs to deliver five packets to reach the same information delivery. In the same way, one needs two 50 Byte packets.

Based on the four groups of results shown in Figures 2 and 3, we can see that almost all the links have a PDR from 0 to 1 within a 10 dBm transmission power difference. In almost all situations, the PDR is higher for

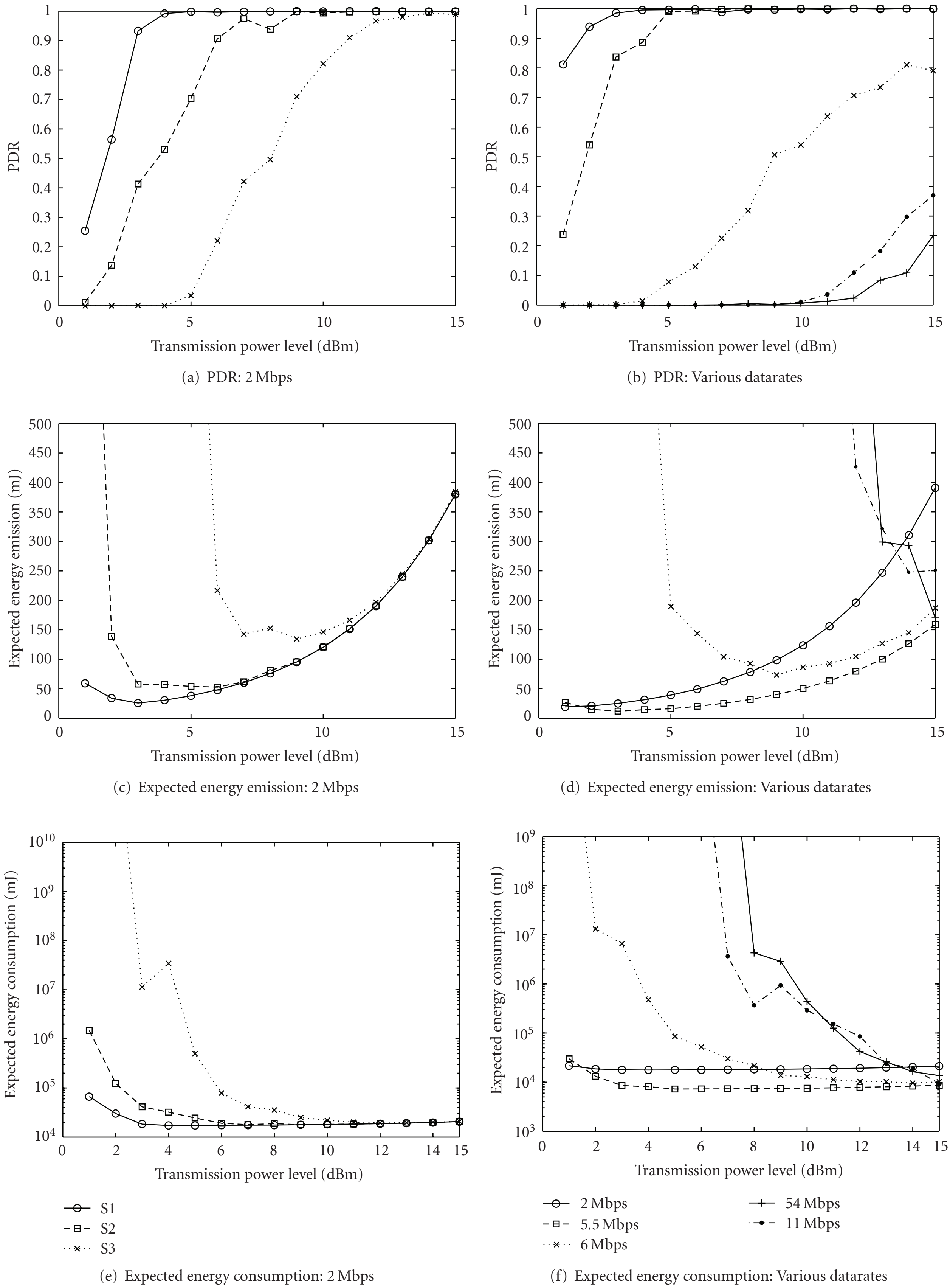


FIGURE 2: The PDR-table and expected energy emission and consumption for IEEE 802.11.

larger transmission power levels. From Figures 2(c) and 3(c), we can see that given a data rate and packet-size, links with better PDR always requires less energy emission and consumption to deliver the same number of packets. However, if we are also able to change the data rate and packet-size, it is possible to further lower the energy emission and consumption.

4. PDR-Based Transmission Power Control

For a certain channel, if the correlation between P, N, and T is known and constant, the best combination can be selected easily. However, the actual channel PDR-table can be quite different from link to link as shown in Figures 2 and 3 and this is also indicated in [3]. Therefore, to have an efficient transmission power control, we need a good mechanism of learning this PDR-table in real time. Meanwhile, the PDR-table may change due to several reasons, such as mobility, environmental changes, and interference. Hence, a self-adapting mechanism is required.

For each link, we need to keep a PDR-table that contains all the N values for the different transmission power levels. The PDR-table may contain values for all possible transmission levels or only a subset of them. The P values are not dynamic and can be calculated beforehand for each of the transmission power level based on the chosen energy model. Since (1) will be used for both the energy emission and consumption calculation, we can use the same transmission power control mechanism for both.

We divided the mechanism into two phases; the initialization phase and the updating phase. The initialization phase tries to quickly learn or "guess" the correlation between the transmit power level and the PDR once a new communication link is established. The updating phase keeps on updating this PDR-table and adapts the transmission power during the whole communication period. The initialization phase should be very short compared to the updating phase. Hence, the initialization phase is more useful for small amounts of traffic and the updating phase is more useful for large amounts of traffic. We describe the two phases in detail in the following two sections.

For neither phase, we do not generate any extra packets to probe the PDR-table. Instead, we use the normal data packets to "learn" the channel and select the appropriate transmission power level. If acknowledgments are being used, which is the case for most wireless links, including 802.11 and 802.15.4, the sender can use them to find out about the packet losses. Otherwise, this information needs to be passed back to the sender in another way. The energy emission or consumption calculation for all methods have the same prerequisite, the same amount of information need to be delivered.

4.1. Initialization Phase. In the initialization phase, different methods can be used to learn or "guess" the correlation between PDR and transmission power level and populate the PDR-table. We propose four initialization methods and compare them with the default method that always transmits with maximum transmission power, which we call "Fixed". We introduce all four methods as follow:

(i) *Default start*. Start using the default power level (15 dBm in 802.11 or 0 dBm in 802.15.4) and then immediately move on to the updating phase. This means only one packet is transmitted and depending on whether it was received or not $N = 0$ or ∞ for the default power level. The remaining Ns in the PDR-table are set to ∞.

(ii) *Sampling*. Send 10 packets in all transmission levels to probe the channel and then use the obtained measurements to build the initial PDR-table and then move on to the updating phase.

(iii) *Historical*. Use the last recoded PDR-table (recorded based on the latest communication record between two nodes). The sender sends 10 small packets (40 Bytes) with full transmission power and the receiver reads and sends back the received signal strength. The sender then compares this with the received signal strength recorded last time. The original table is shifted left or right with the difference value based on the signal strength difference and forms the new PDR-table.

(iv) *Combined*. First collect the received signal strength as in the Historical method. If the signal strength between now and the previous communication are similar (within 2 dBm difference), the Historical method is used. Otherwise, the Sampling method is used.

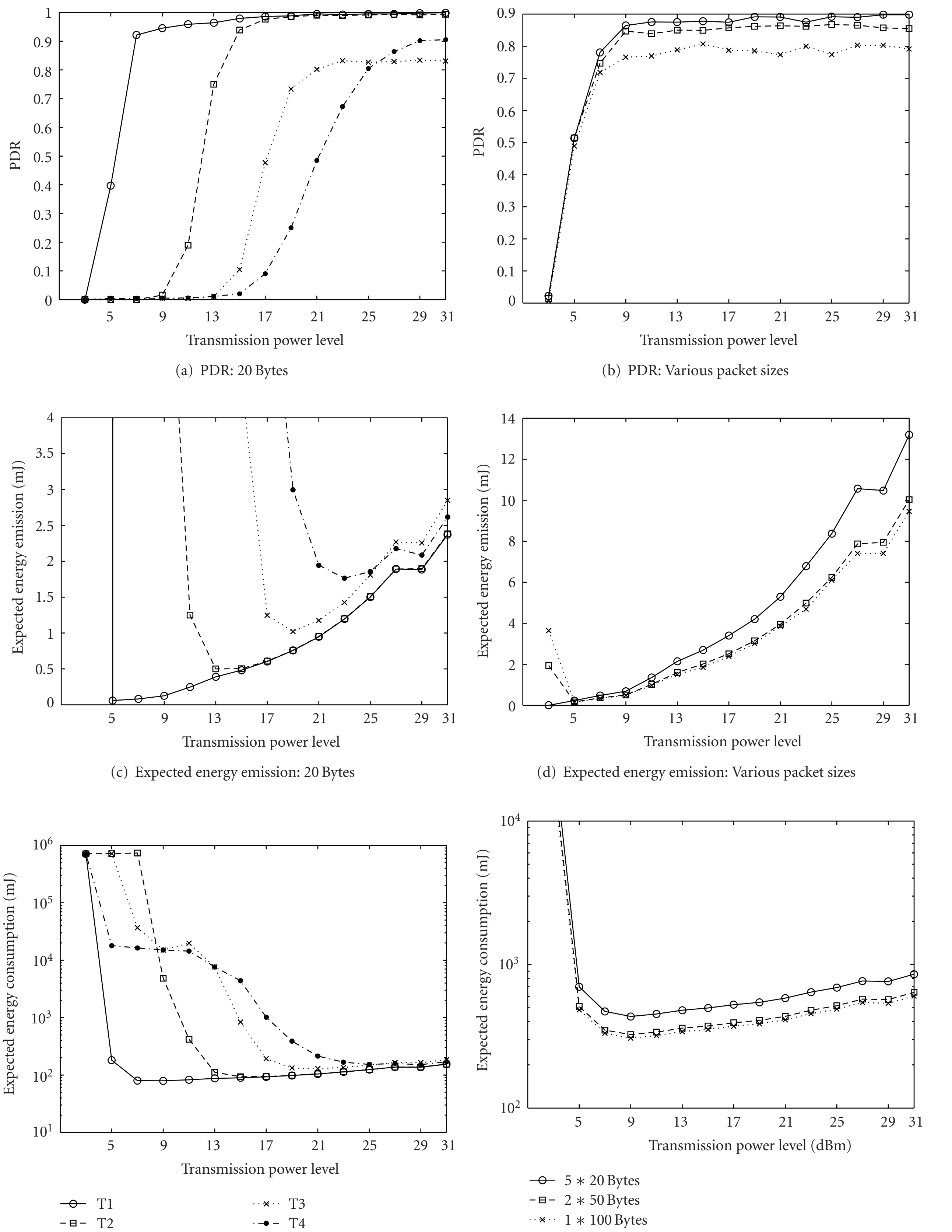
A better initialization method starts closer and converges faster to the optimal transmit power. In Section 6.1.1, we will compare all these methods with the Fixed method, which sends all packets with default power level during both the initialization and updating phases and hence makes no use of the PDR knowledge.

4.2. Updating Phase. In the updating phase, most packets are transmitted with the transmission power level that minimizes (1). If two levels have the same power consumption, then the higher transmission power level will be used.

The estimated PDR for the other power levels also needs to be updated, since the whole PDR-table is dynamic if the link changes. Therefore, we propose to send a certain percentage of packets using a randomly selected power level other than the current one. In this way, the estimated PDR for all power levels can be updated. Periodically, we calculate the PDR for each level by dividing the number of received packets with the number of sent packets during that period. To have a controllable smooth updating process for all the information, we use an EWMA method as in (5),

$$E_{t+1} = \alpha X_t + (1 - \alpha)E_t, \tag{5}$$

where the E_t means the current estimation of PDR for a certain transmission power level in interval t, X_t is the calculation of PDR for this power level in interval t, and the smoothing factor α is used to tune the speed of updating.



(a) PDR: 20 Bytes

(b) PDR: Various packet sizes

(c) Expected energy emission: 20 Bytes

(d) Expected energy emission: Various packet sizes

(e) Expected energy consumption: 20 Bytes

(f) Expected energy consumption: Various packet sizes

Figure 3: The PDR-table and expected energy emission and consumption for IEEE 802.15.4.

This is only done for N values that had a transmission in the PDR-table during the interval. We used an interval of 10 packets.

We defined another parameter which controls the probability that a packet will use another level than the selected optimal level. This probability is defined as β. The level to probe is selected uniformly among the other levels in the PDR-table. The performance of the updating phase with different α and β is investigated in Section 6.1.2.

5. Experimental Setup

All experiments were carried out in a typical indoor office environment. They were done at night when there were very few people walking around. For each scenario, we collected a packet trace and used a post processing approach to compare every method and parameter. In this way, every parameter combination could be compared based on the same actual link in a fair way.

5.1. IEEE 802.11 Test-Bed. For all our IEEE 802.11 experiments, we used two HP laptops (HP7400) equipped with 3Com 108 Mbps 11g XJACK PC wireless cards. Linux 2.6 and the Madwifi driver version 0.9.4 were used. We specially wrote a one-hop communication program, which had a sender and a receiver part. The node running the sender program controlled the transmission power level for each packet transmission. A fixed packet-size (1500 Bytes) was used during all experiments. We used broadcast packets to avoid MAC level retransmissions and the receiver side recorded the number of received packets. In a real system, feedback from the retransmission mechanism can be used instead.

We used channel 7 during the experiments. Long duration observations were done of the noise level for this channel and the value was around −96 dBm with a maximum variance of 2 dBm. Different distances (8, 16, and 20 meters, resp.) were used in the experiments to generate different channel conditions, but always nonline of sight (NLOS). We name these scenarios as S1, S2, and S3. For the experiments with different data rates, we used a distance of 20 m with another NLOS channel. Therefore, we call it S4.

5.2. IEEE 802.15.4 Test-Bed. We used an IEEE 802.15.4 compliant device in the 2.4 GHz ISM band from Moteiv, called Tmote sky that uses the CC2420 wireless chip [16]. During the experiment, the USB was used as power supply. As in IEEE 802.11, we also wrote a one-hop communication program for these devices. We used three different payload sizes. They were 20, 50 and 100 Bytes. IEEE 802.15.4 has a packet header, which consists of 11 Bytes of PHY header and 6 Bytes MAC header. The standard data rate (250 kbps) was used during all experiments. We used only 15 different transmission power levels for the Tmote to be more comparable with our 802.11 experiments. Since there are 31 possible levels, we only used the odd levels between 3 and 31. Based on [16], they correspond to dBm as follows: Level 3 corresponds to −23 dBm, level 31 to 0 dBm and the levels in between are mapped in an almost linear fashion.

All the experiments were done in a channel that did not interfere with any IEEE 802.11 radio. We also did experiments in a channel that was impacted by IEEE 802.11 radio interference and found that the result was not much influenced. We used broadcast packets in the same way as in IEEE 802.11. We recorded the number of received packets and the used transmission power levels.

The IEEE 802.15.4 experiments were done in the same location as for IEEE 802.11, however, different distances were used. All channel were NLOS and the distances were 12, 14, 16, 18 m, respectively. We call these experiment scenarios T1 to T4. The experiments with different packet-sizes were done with 17 m between the sender and receiver with a NLOS channel.

5.3. Experiment Methodology. For each scenario, we collected a data trace by sending 30000 packets with different power levels during a period of 20 minutes. To be able to compare fairly between different methods and parameters, we used a post processing approach. In this approach, we took the trace and divided it into 200 batches. Each batch contained 150 packets, 10 packets of each power level. For each method and parameter combination, we emulated the process. This was done by assuming that only 10 packets were sent from each batch and it was up to the method to decide which power levels to pick. That is, for each emulation, only a fraction of the trace was used.

For the updating phase, $(1 - \beta)\%$ of the 10 packets were assumed to be transmitted with the currently selected best power level and $\beta\%$ were assumed to be sent for probing the other power levels. These assumed packets were randomly selected from the trace, based on the power level and the batch it belonged to. From the trace, we checked whether the selected packets were received or not and used this information in the method. An important issue is that, due to the limited number of packets on each nonbest transmission power level (e.g., $10 \cdot 10\%$ for each interval is only 1 packet), the PDR for each transmission power level is only updated when there is a packet transmission in this interval. Since this random selection introduces variance, we repeated this process 300 times and calculated the mean and 95% confidence interval.

Parts of the packets are sent in the initialization phase and parts are in the updating phase. Each transmission was done with a certain transmission power level and took a certain duration. Therefore, the total energy emission or consumption was the sum of all energy emitted or consumed for all the transmissions. We processed the data using this method several times and due to some random factors in the processing, the total energy emission from each processing are hardly exactly the same. However, they are quite similar and the confidence intervals are very small, so we did not plot them and only plotted the average expected energy emission for a certain method and parameter combination. We did the same processing for the updating phase as well.

Unfortunately our IEEE 802.11 card did not support fast power variation. Based on measurements, we could conclude that it took our card about 1 second to change from the highest to the lowest transmission power level. Hence, we divided the time into intervals, each of 8 seconds long. In each interval, we first transmitted 200 packets with one transmission power level and then paused for two seconds. Right after the pause, we modified the power level to the next level and waited two seconds. The power level was changed in a round robin fashion between all 15 levels. For IEEE 802.15.4, we changed the power level per packet, which caused no problems.

6. Performance Evaluation

In this section, we evaluate the performance of our PDR-based mechanism. The energy emission and energy consumption are discussed in the following two sections, starting with the energy emission. In Section 6.3, we look at strategies to optimize both.

6.1. Energy Emission Reduction. First, we present the emission reduction results for both the initialization and updating phases.

6.1.1. Initialization Phase. The target of the initialization phase is to quickly populate the PDR-table and select a good transmission power level to start with and then enter the updating phase as explained in Section 4.1. In this comparison, a fixed α value of 0.2 and a fixed percent of probing packets of $\beta = 10\%$ were used in the updating phase. We tried different α and β values in Section 6.1.2. For the Historical method, we used the PDR-table learned from the same location one day earlier. In Figure 4, we present an example of how each initialization phase selects the best transmission power level in each batch for IEEE 802.11. We can see that all methods, except Fixed, converge to the best transmit power level (around 2 dBm) after no more than 50 batches (corresponding to 500 s or 500 transmitted packets).

We calculated the total expected energy emission for the first 60 batches of each method and present the results in Figure 5. The number of 60 batches is selected due to the reason that after this time, all the methods definitely go to the updating phase. The expected energy emission means the required energy needed to be generated to the environment to deliver a certain amount of information, that is, to successfully transmit all 2000 packets. We can see that all our proposed initialization methods can reduce the energy emission compared to the Fixed method. The Historical and Sampling methods can further reduce the energy emission compared to Default start. The Combined method achieved the best performance, which indicates that using an accurate PDR-table is essential for a good initialization phase.

6.1.2. Updating Phase

(i) *IEEE 802.11.* For the updating phase, we need to find the optimal α to use in (5). To have a fair comparison of

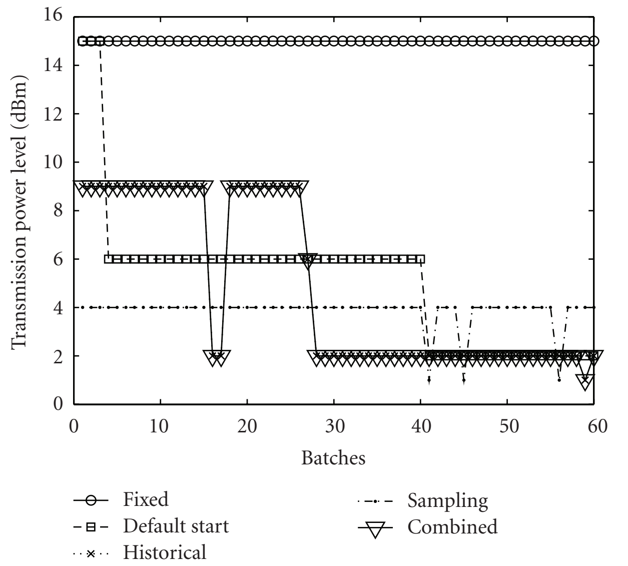


FIGURE 4: The selected best power level in each time interval by different methods in scenario 1 (IEEE 802.11).

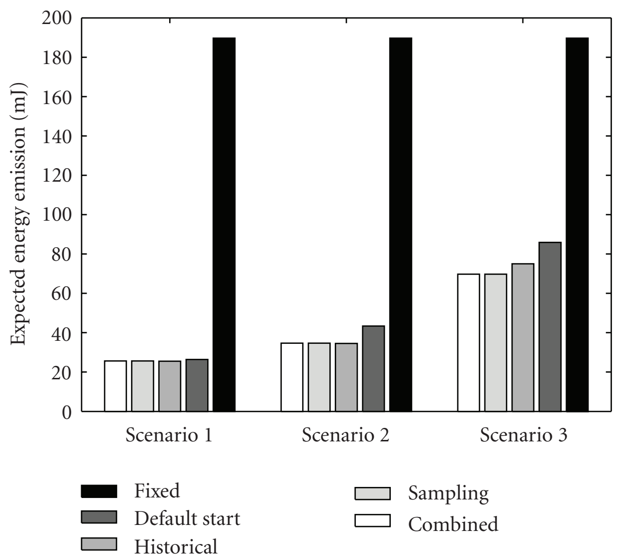
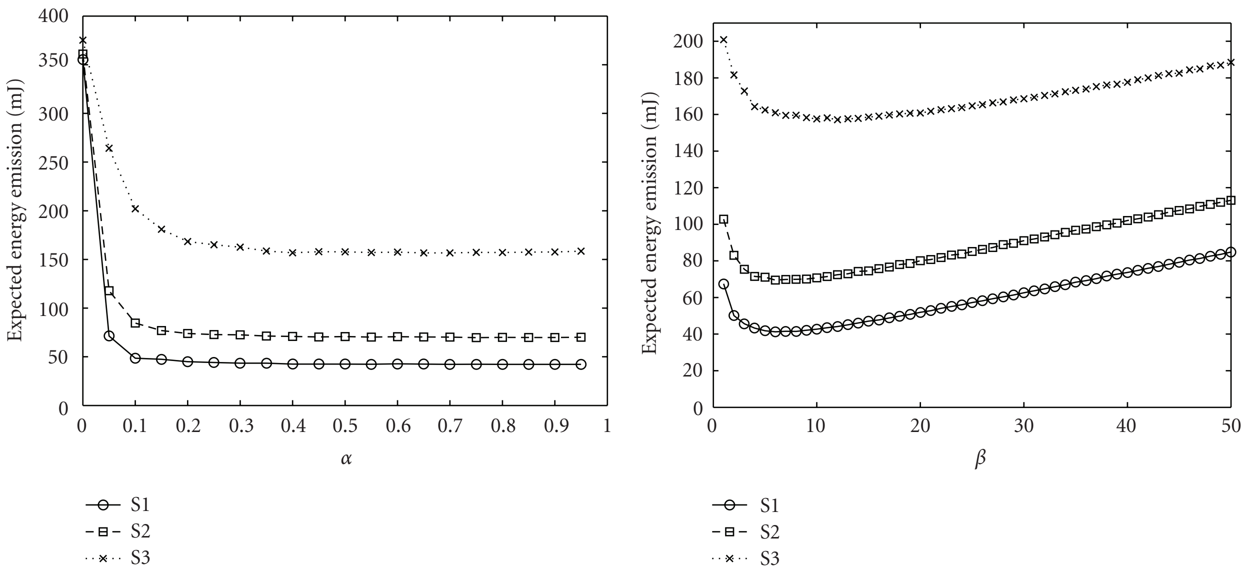


FIGURE 5: The initialization phase performance comparison (IEEE 802.11).

all different α values, we fixed all the other parameters. The percentage of probing packets, β, was set to 10% and we used the Default start method. For each α value, we calculated the average expected energy emission of 300 experiments and show the result in Figure 6(a) based on all 200 batches from the trace. We can see that when $\alpha > 0$, the energy emission decreases compared to when no updating is done ($\alpha = 0$, always using 15 dBm) and that different links have different optimal α. We can also see that when $\alpha > 0.2$, no major improvements can be seen. Since a smaller α is better for mobile scenarios, we propose to use $\alpha = 0.2$.

Another parameter to investigate is β. Figure 6(b) shows the results of using $\alpha = 0.5$ and different amounts of probing



(a) best α

(b) best β

Figure 6: The best α and β for IEEE 802.11, 2 Mbps.

Table 1: Quantitative comparison of expected energy emission for the updating phase: IEEE 802.11.

Scenario	S1	S2	S3
Fixed (mJ)	379.44	379.44	379.44
PDR-based (mJ)	41.87	67.78	161.42
Reduction	−89%	−84%	−57%

packets. We can see that for each scenario, the optimal β values for each link are all between 5 to 10%, which suggests that we should not send too many packets to probe other transmission power levels. However, the optimal β is different for each link. The general rule is that, when the link is worse (PDR is lower for most power levels), the optimal β is larger, which suggest that for lossy links, more probing should be done. However, a value of 10% performs well enough for all scenarios.

Using $\alpha = 0.2$ and $\beta = 10\%$, we made a general comparison in Table 1 between the PDR-based method and the Fixed method of always using 15 dBm. Default start was used in the initialization phase. We can see that for each scenario, the energy emission is much less than for the Fixed method.

(ii) *IEEE 802.15.4.* We used the same processing code to process the results for IEEE 802.15.4, but with the traces from scenario T1 to T4. To have a fair comparison of all different α values, we fixed β at 10%. We used the maximum transmission power level (31) to start. Based on Figure 7(a), we can see that we got similar results as in Figure 6(a). When α is larger than 0.1, the expected energy consumption is much smaller than the expected energy consumption when α equal to 0. There is not much difference when α is larger than 0.1.

We further processed the measurement results with the assumption that α is equal to 0.5 and we compared the expected energy emission with different β values, from 1 to 50. The results are shown in Figure 7(b). The optimal β value for $\alpha = 0.5$ is around 5% and more probes will result in more energy emission.

To have a better comparison between different α and β in each scenario, we calculated all the combinations for α values from 0 to 1 in steps of 0.05 and β values from 1 to 50 in steps of 1.0. In Figure 8, we use a 3D graph to show the expected energy emission for all combinations. A common trend is that when $\alpha = 0$, which means no update at all and always use the highest transmission power level, the energy emission is much larger compared to when $\alpha > 0$. In Figure 8(a), we can see that it is very obvious that larger β values will result in more energy emission. This is because the optimal transmission power level is 5 and higher power levels will cost more energy for each transmission. Most power levels are not worth to be probed, therefore, a larger β results in more energy waste. When the channel becomes worse, the expected energy emission with different β is less, which is most obvious in Figure 8(d). Another interesting result is that there are more fluctuations when α or β increase in scenarios with worse channels, which can be seen in Figure 8(d).

Similar to Table 1, we calculated the total energy emission for each scenario with $\alpha = 0.2$ and $\beta = 10\%$ and present the results in Table 2. The best α and β values are also included in the table. We can see that the PDR-based method only emits about 20% to 53% percent of the energy compared to the Fixed method. We also present the values based on the optimal α and β selection from Figure 8. We can see that in most cases, we are very close to the optimum simply by using $\alpha = 0.2$ and $\beta = 10\%$, which means we can use this combination for almost all the scenarios.

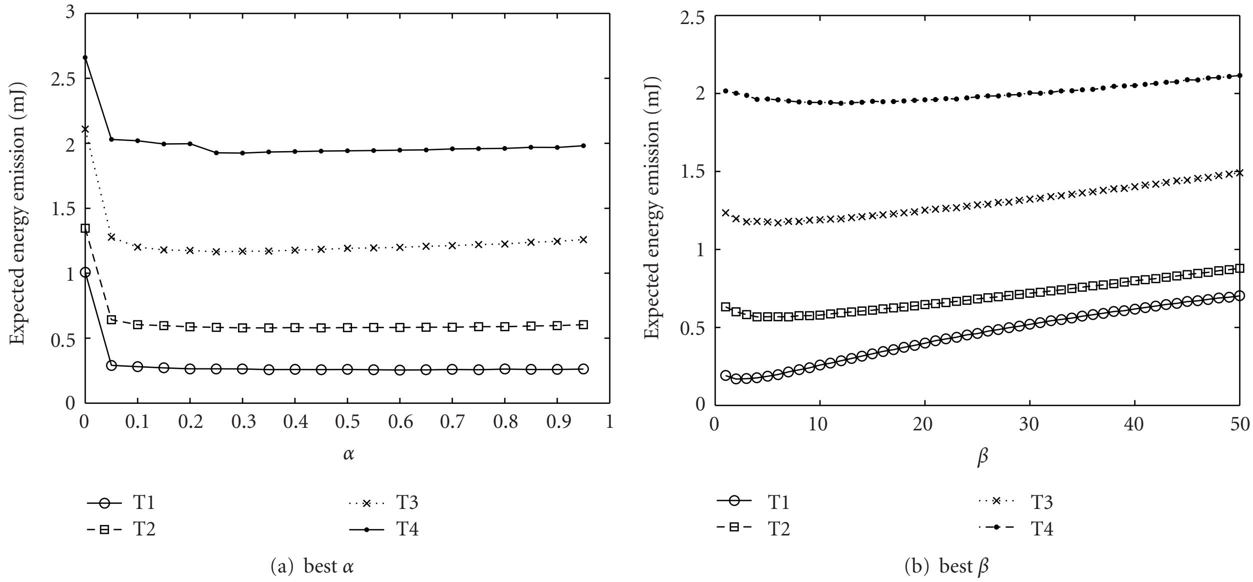


Figure 7: The best α and β for IEEE 802.15.4, 20 Bytes.

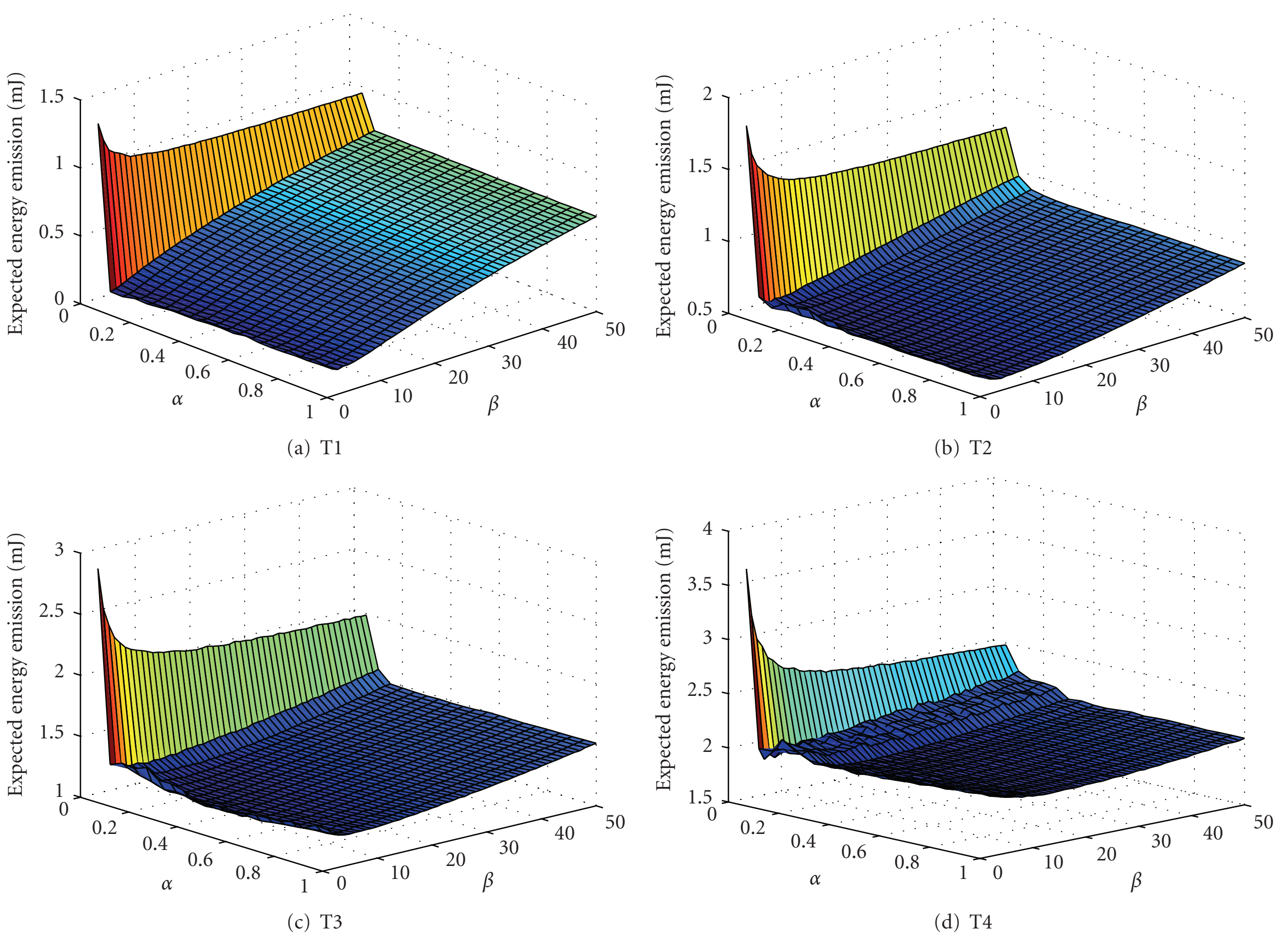


Figure 8: 3D α and β combinations for different Scenarios (802.15.4).

Table 2: Quantitative comparison of expected energy emission for the updating phase: IEEE 802.15.4.

Scenario	T1	T2	T3	T4
Fixed (mJ)	1.3496	1.8223	2.8932	3.6682
PDR-based (mJ)	0.2735	0.5865	1.1863	1.9430
Reduction	−80%	−68%	−59%	−47%
PDR-based (optimal) (mJ)	0.1428	0.5621	1.11572	1.9118
Optimal α	0.15	0.5	0.35	0.35
Optimal β	2%	10%	14%	28%

6.1.3. Impacting Factors for the Updating Phase. The results presented in Section 6.1.2 are all with the same configuration for different scenarios. To make it more practical to the real world, we further evaluated the performance of the updating phase by studying factors that may influence the performance, such as transmission data rate, packet-size, mobility, and time dependence.

(i) *Data Rate.* IEEE 802.11 offers multiple data rates. Based on different channel conditions, different modulation and coding schemes can be used to achieve the highest throughput. The main question is whether the results in Section 6.1.2 are valid for other data rates or not. Moreover, from the energy emission perspective, the highest throughput data rate may not be the one that saves the most energy. We post processed the measurement traces shown in Figure 2(b) to see the impact of α and β and display it in Figure 9(a).

We can see that for the three experiments with lower data rates (2, 5.5, 6 Mbps), the effect is the same as in Figure 6(a). However, for the high rates (11, 54 Mbps), due to the lower PDR at almost all the transmission power levels, the updating phase cannot do much to reduce energy emission and 15 dBm is optimal. Therefore, α does not have much impact on the performance. Since these experiments were done in the same location, we can see that 5.5 Mbps is the most power saving data rate. However, if we change to another location with another distance, another data rate may be optimal, which suggests that not only the transmission power level, but also the data rate can be selected to save power.

Concerning β, low data rates need more probe packets to update the PDR information. For the higher data rates in this experiment, most other power levels will directly result in packet drops. Therefore, probing more on other power levels increases the expected energy emission. In other scenarios, this may not be the case.

(ii) *Packet Size.* It is also important to know the performance with different packet-sizes. In order to experiment with different packet-sizes over a similar link, we used 802.15.4 and changed the packet sending method. For each packet-size, we sent 30000 packets in 200 batches. We splitted each of the three different packet-size experiments into 10 equalled sized parts and we interleaved the parts of the experiments in a round robin fashion. In this way, the three packet-sizes experiment are experiencing very similar channel conditions. By interleaving, we mitigate unfairness caused by slowly changing link conditions.

We again calculated the best α and β using our post processing method and got the results in Figure 10. For the best β, the conclusion is similar as previously. However, it is interesting to see the result for the best α. When $\alpha = 0$, the energy emission is still very high. However, a larger α will have less energy emission. To deliver the same amount of information, a larger packet-size emits less energy in this scenario.

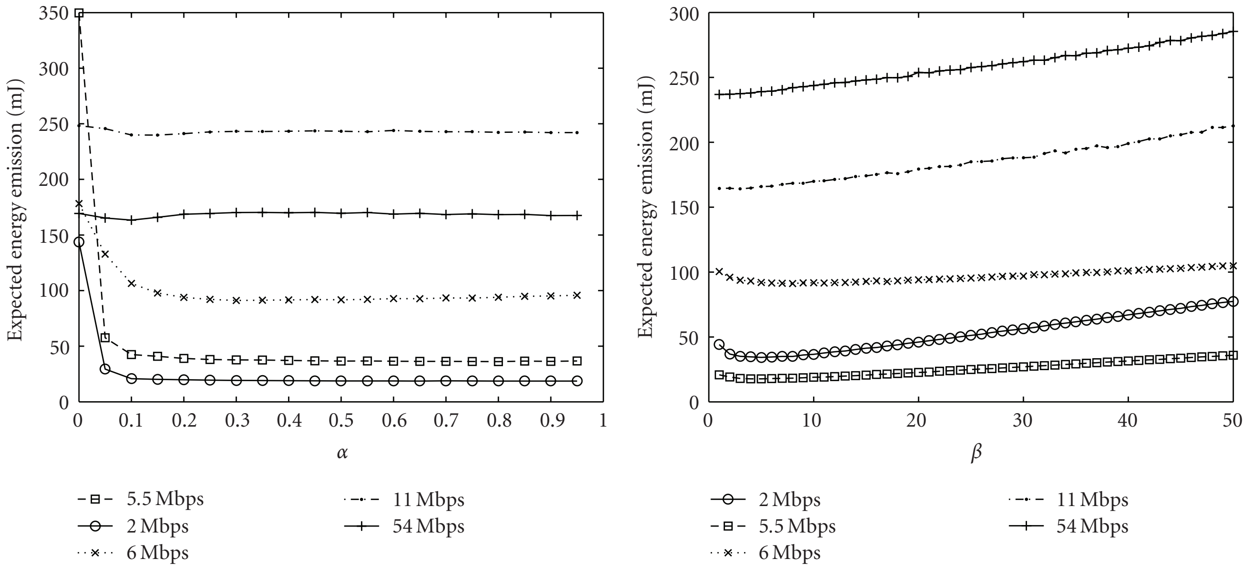
(iii) *Mobility.* Since all the scenarios are stationary, we still need to investigate the performance in a mobile environment. Instead of moving the devices around, which is time consuming and difficult to replicate between experiments, we emulated a mobile channel by stitching together the traces from scenario T1, T2, and T3. The way we generate mobility is not ideal, but it still gives us some insights. It shows how channel variance can affect the selection of α and β, which is our interest.

The measurement results were segmented into different numbers of batches based on different mobility level assumptions. The mobile channel went from good (T1), to medium (T2), to bad quality (T3). To emulate different amount of mobility, we stayed with the same scenario data for different amount of time before changing to the next scenario trace. We used four different PDR change speeds, which we measured in number of batches. A mobility scenario which changes trace every 10 batches, that is, Mobility-10, is more mobile than one which changes only every 100 batches, that is, Mobility-100.

We plot the performance of different α for different mobility levels in Figure 11. We can see that for low mobility levels, for example, Mobility-100, the best α is not big. When the mobility level increases, the best α also increase. This conclusion does not hold for the situation with Mobility-10, in which the mobility is quite high. It is interesting to note that despite different mobility levels, the expected minimum energy emission remains similar. Less mobility will decrease the minimum expected energy emission, but not significant.

We also plotted all the combinations of the α and β for different mobility levels with 3D graphs in Figure 12. The results are similar to the previous 3D results in Figure 8. However, it is obvious that with higher mobility, the best α value gradually increases, except for Figure 12(a). Perhaps somewhat surprising, different mobility levels do not cause too much impact on the optimal β value. Furthermore, the minimum expected energy emission is similar for all levels of mobility. Hence, mobility does not affect α and β very much.

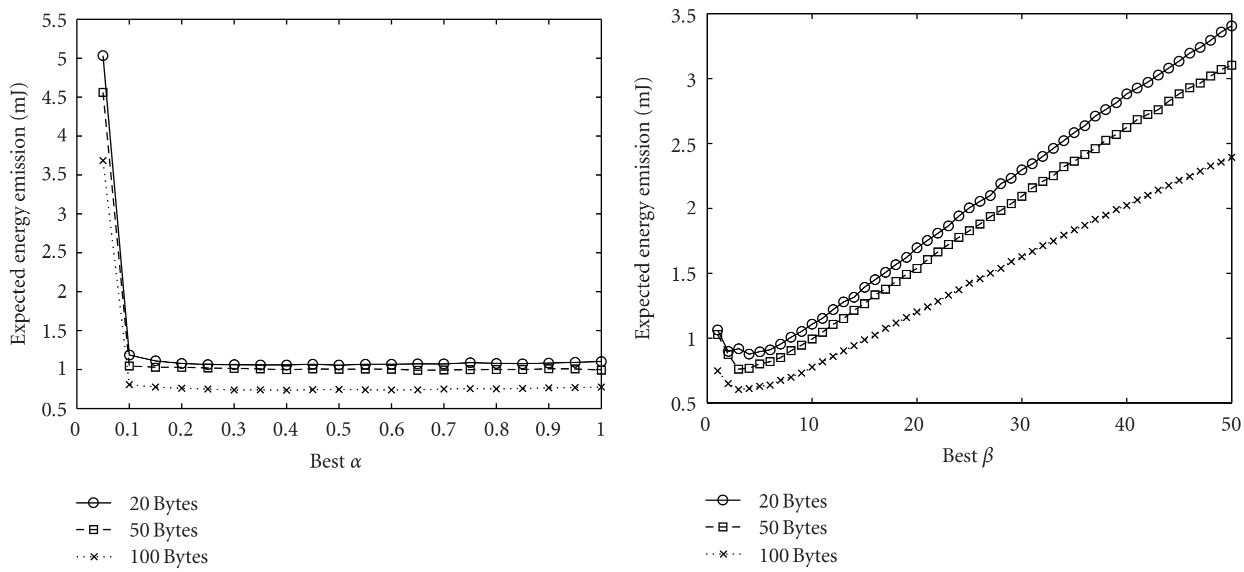
(iv) *Variance over Time.* To study the change of the optimal α value over time, we segmented the experiments into 5 different pieces in the time domain and used the same method as previously to select the best α for each piece. The results for both IEEE 802.11 and 802.15.4 are shown in Figure 13. We found that the optimal selection for α changes over time for all links. However, the difference in energy emission between the different α values is not significant,



(a) best α

(b) best β

Figure 9: The best α and β for IEEE 802.11 with difference data rates.



(a) best α

(b) best β

Figure 10: The best α and β for IEEE 802.15.4 with difference packet-sizes.

given the results in Figure 6(a). Therefore, in practice, one should just stick to one fixed α as long as $\alpha \geq 0.1$. For IEEE 802.15.4, the variance of the optimal α is larger over time, but still the energy emission difference is small as shown in Figure 7(a).

6.1.4. Discussion. Although all experiments were done with only changing the transmission power levels, our PDR-based method can also be applied to multi-factor environments. For example, we can keep records of three different data rates (or packet-sizes) but only five different power levels instead of all 15. The selection would then involve finding the most optimal rate (packet-size) and power level combination. It is also obvious to see that if proper α and β values are selected, the energy emission can be reduced in most scenarios.

6.2. Energy Consumption Reduction. Since energy saving is more important for IEEE 802.15.4 devices, we also need to look at reducing the energy consumption by means of selecting the transmission power level. To do this, we used the trace files of the IEEE 802.15.4 radios from scenario T1, T2, and T4. However, we replaced the energy model and

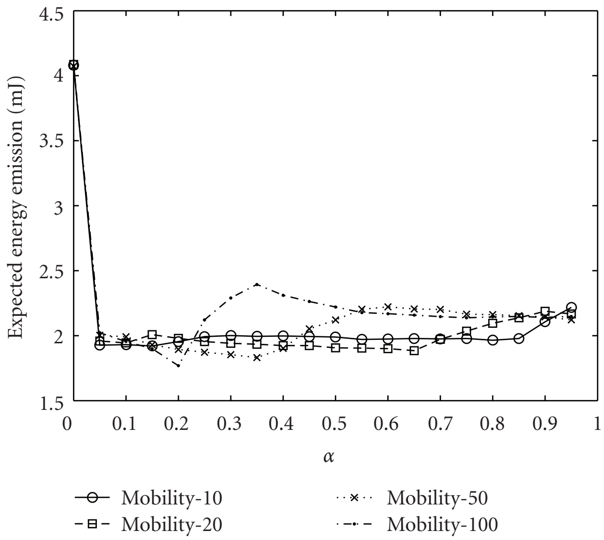


Figure 11: The best alpha value with different levels of mobility.

used $P = 35 \cdot P_{\mathrm{RF}} + 30$ instead. Then we did the same experiments as in the previous section. We show the results in Figure 14 and we can see that we got similar conclusions with respect to α and β as the results in Figure 7. The main difference is that the expected energy consumption is much larger than the expected energy emission due to the fact that most consumed energy is not emitted. Due to the similarity of the results, we do not present more results for the energy consumption calculation for other situations. Instead, to better demonstrate the effectiveness of our mechanism, we compare it with a typical signal strength-based algorithm proposed in [15]. We used their *aggressive method* in our comparison, since it was claimed by the authors to have better performance. We briefly introduce their mechanism as follows.

The mechanism uses the received packets' signal strength to adapt the transmission power level. This received signal strength is denoted as R. An EWMA method (see (5)) is used to smooth R with $\alpha = 0.8$ and then denoted as $\widehat{R}$. Every time a packet is received, $\widehat{R}$ is updated and then one of the following is done:

$$\begin{aligned} &\text{if } \widehat{R} < T_L, \quad \text{double the transmit power;} \\ &\text{if } T_L \le \widehat{R} \le T_H, \quad \text{keep the same transmit power;} \\ &\text{if } \widehat{R} > T_H, \quad \text{reduce the transmit power by a constant;} \end{aligned} \tag{6}$$

where $T_L = -85$ dBm and $T_H = -80$ dBm for our wireless chip CC2420 according to [15].

During the implementation, we found that there is a logical error in the mechanism. If a packet is lost, no new signal strength value will be read and $\widehat{R}$ will not be updated. If, at the same time, $\widehat{R} > T_L$, the transmission power will not be increased and this can lead to a deadlock. This situation could be quite possible, especially in mobile scenarios. Therefore, we adapted their method by letting a lost packet have an assumed received signal strength of −95 dBm, the lowest receivable signal strength for CC2420.

Table 3: Quantitative comparison for the energy consumption of IEEE 802.15.4.

Scenario	T1	T2	T4
Fixed (mJ)	154.0	154.8	169.9
Signal strength-based (mJ)	121.6	154.8	169.9
PDR-based (mJ)	79.9	130.2	164.1

Furthermore, the authors do not specify the constant used when decreasing the transmission power level. In our implementation, we decrease the power by one level (corresponding to a decrease between 1 dBm and 3 dBm depending on the levels) when $\widehat{R} > T_H$.

To compare the two mechanisms, we used scenario T1, T2, and T4. The same trace data was used, since we also recorded the received signal strength. The results are shown in Table 3. We can see that the PDR-based method outperformed both the Fixed method and the signal strength method. Our PDR-based method always saves energy compared to the Fixed method, meanwhile, the signal strength-based method sometimes performs worse. This is because it only focuses on signal strength and ignores packet loss and at the same time, packet loss increases so much that the increased number of retransmissions cancels out the lower power consumption of using a lower transmission power level.

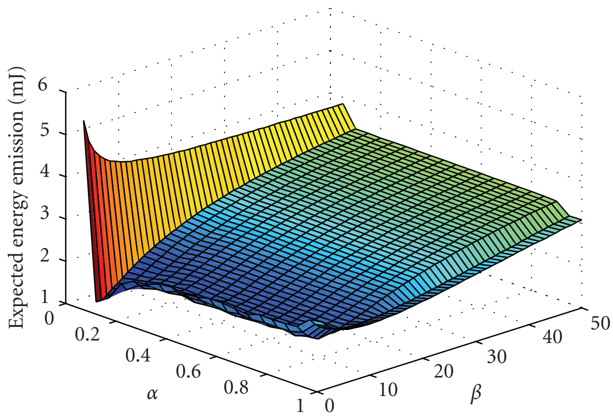
The reason why the PDR-based method performs better is its direct use of the PDR to power level correlation. The signal strength-based method uses fixed thresholds for all the scenarios, which may work in some cases, but not in others, such as T1 and T2. The correlation between received signal strength and packet loss is simply too weak.

To show the reason behind the good performance of the PDR-based method, we show in Figure 15 the transmission power level distribution for both methods in scenario T1 and T2 as examples. Also compare these results with the PDRs for these levels shown in Figure 3(a) and the energy consumption shown in Figure 3(e). We can clearly see that the signal strength method always use the maximum power level in scenario T2, which is the same as the Fixed method. The same happens in scenario T4 (not shown). Only in scenario T1, it shows some "smarter" selection. For the PDR-based method, we can clearly see that the transmission power level used for most packets are close to the optimal level 7 (see Figure 3(e)).

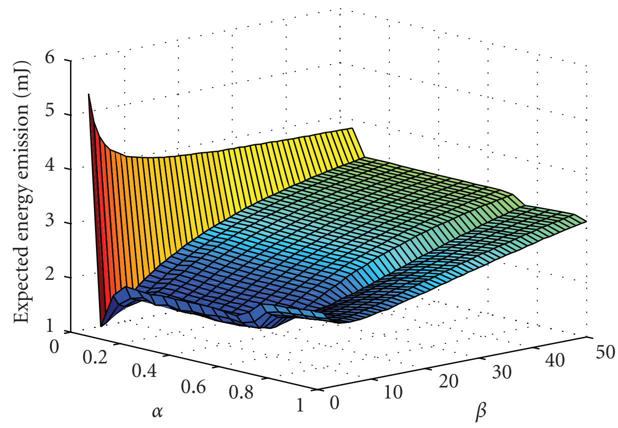
6.3. Trade-Off between Energy Emission and Consumption. In some cases, a trade-off between minimizing the energy emission and the energy consumption may be sought. To allow for this, we introduce a tunable parameter ω as follows.

When comparing (2) with (3) or (4) and given that a multiplicative scalar does not affect the end result, we may capture all optimization functions with the following equation:

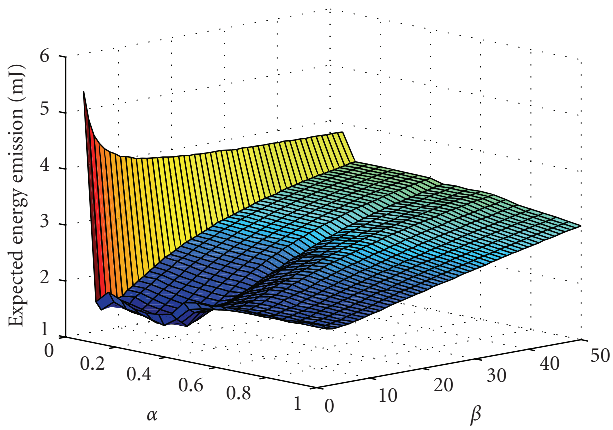
$$P = P_{\mathrm{RF}} + \omega, \tag{7}$$



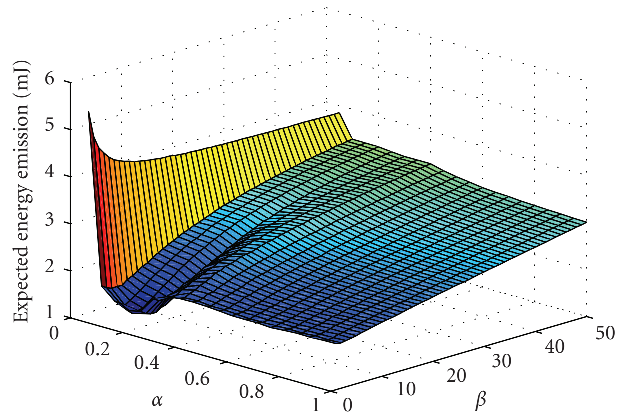
(a) Mobility-10



(b) Mobility-20

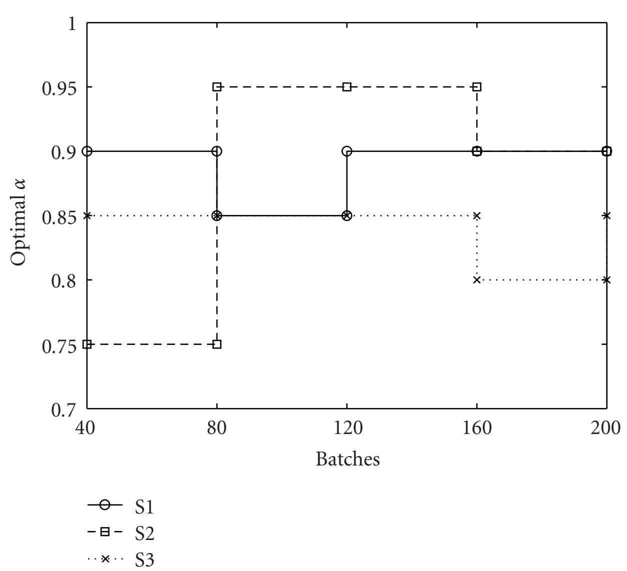


(c) Mobility-50

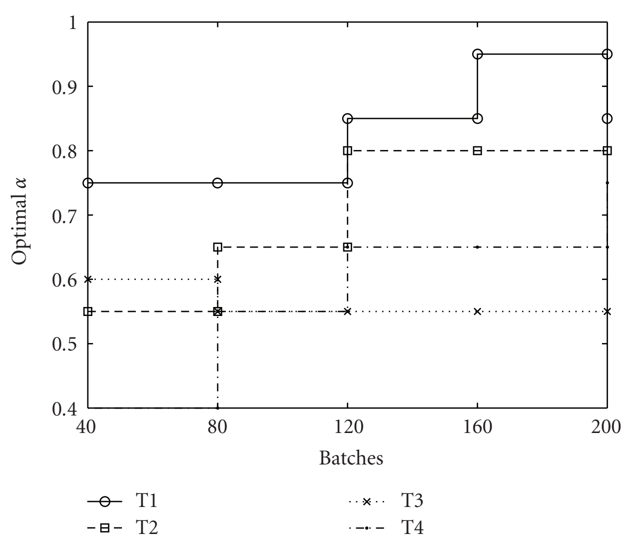


(d) Mobility-100

FIGURE 12: α and β combinations for different mobility levels.



(a) IEEE 802.11



(b) IEEE 802.15.4

FIGURE 13: The best α with time for IEEE 802.11 and IEEE 802.15.4.

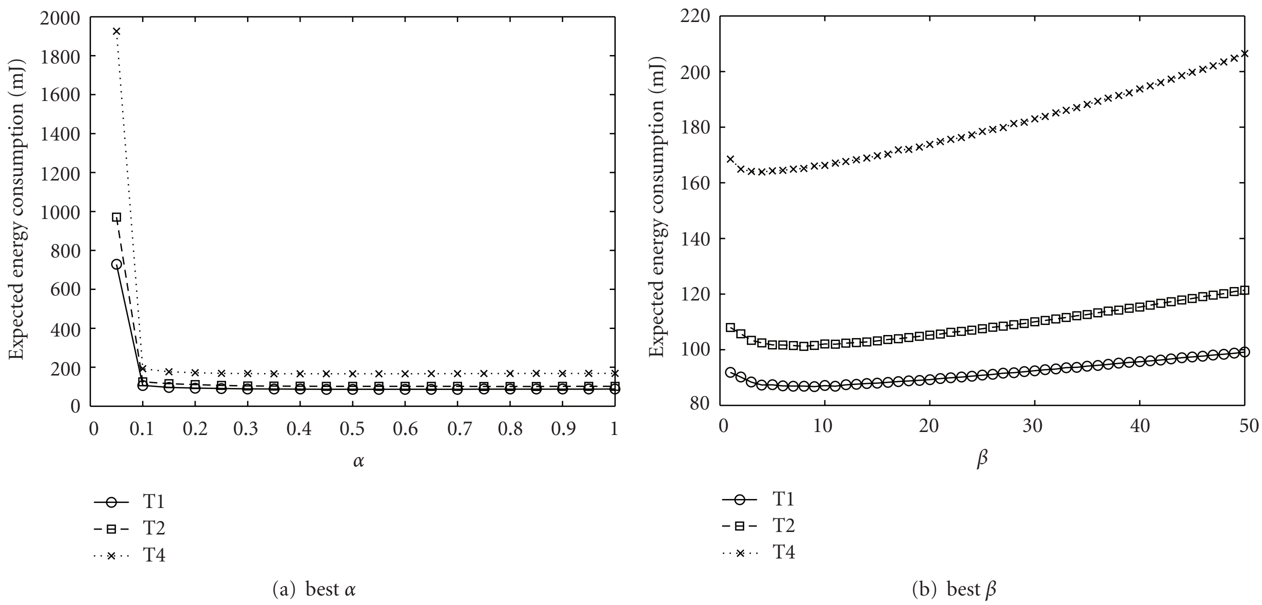


Figure 14: The best α and β for IEEE 802.15.4 energy consumption, 20 Bytes.

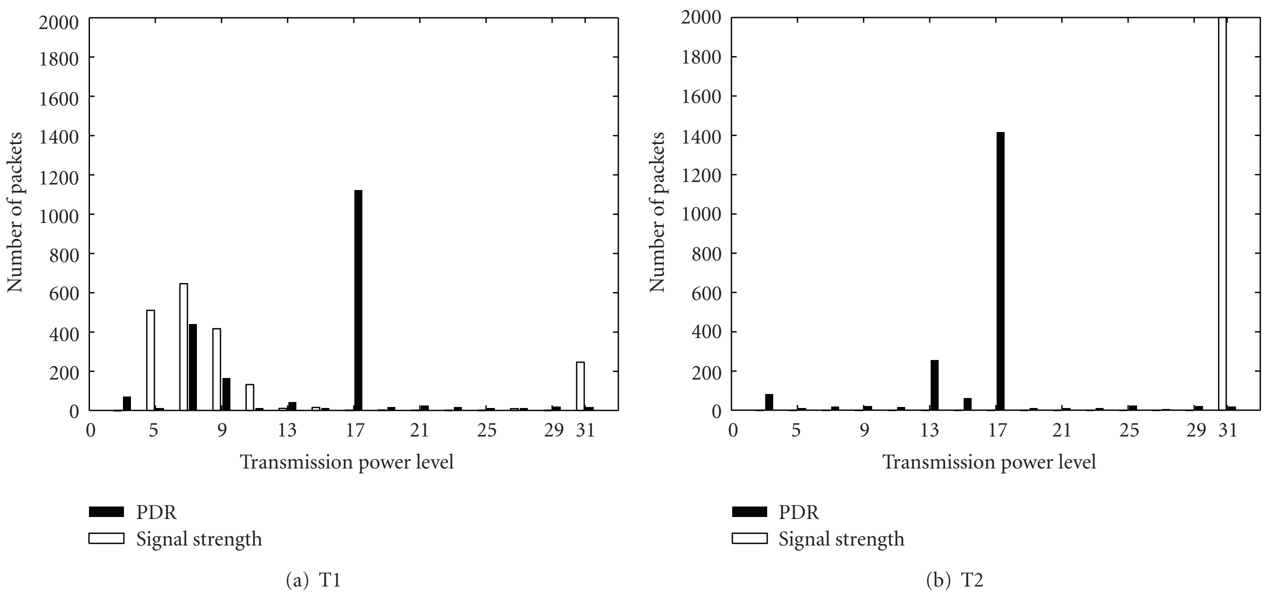


Figure 15: The transmission power levels distribution for the proposed and signal strength-based algorithms in the two scenarios.

where $\omega \in [0, 1400/10]$ for IEEE 802.11 or $\omega \in [0, 30/35]$ for IEEE 802.15.4. If we set $\omega = 0$, we get (2) and will optimize for energy emission. If we set $\omega = 1400/10$ for IEEE 802.11 (or $\omega = 30/35$ for IEEE 802.15.4), we optimize for energy consumption. However, it is also possible to set ω to a value in between and that would mean that we get a trade-off between energy emission and energy consumption.

To demonstrate how this tuning works, we used the T1 scenario as an example and calculated the expected energy consumption and emission with different ω values. The result is plotted in Figure 16. We can see how different ω values affect the energy emission and energy consumption for this scenario. By making ω smaller, we reduce the energy emission, while the energy consumption increases and by making ω larger, we reduce the energy consumption, while the energy emission increases. Hence, we can use ω as a tuning parameter.

We can also use ω to control the expected delay. A larger ω will penalize a lost packet more and this causes a higher

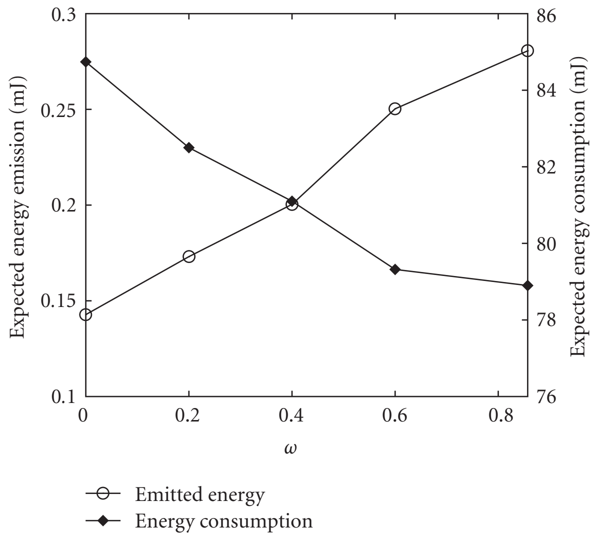


Figure 16: Trade off between minimum energy consumption and energy emission.

power level to be chosen. The effect is fewer packet losses, fewer retransmissions, and thereby less delay.

7. Conclusions

Energy emission and consumption reduction are key challenges for wireless networks. In this paper, we proposed to select the appropriate transmission power level using PDR information in order to reduce the energy emission and/or consumption. We proposed to use the EWMA method to update the PDR and transmission power level correlation and use this to adapt the transmission power. We proposed four initialization phase methods to get a good transmission power level to start with. Furthermore, we investigated the optimal parameters for this correlation in order to achieve minimum energy emission or consumption. Different impacting factors were also analyzed. We carried out measurements in two types of test-beds and showed that a significant amount of energy can be saved for the transmitter in typical scenarios. We also compared our mechanism with a signal strength-based mechanism and showed improved energy savings. Finally, we demonstrated that our mechanism can be tuned to achieve a balance between the minimum energy consumption and emission, which enables the user to adaptively set the desired target.

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