ATPS: Adaptive Transmission Power Selection for Communication in Wireless Body Area Networks

Abbas Arghavani, Haibo Zhang, Zhiyi Huang, Yawen Chen
Department of Computer Science, University of Otago, Dunedin, New Zealand
Email: {arghavani, haibo, hzy, yawen}@cs.otago.ac.nz

***Abstract*—Since radio links in wireless body area networks (WBANs) commonly experience highly time-varying attenuation due to topology instability, communication protocols with fixed transmission power cannot produce a very good performance in terms of energy consumption, interference range, and communication reliability. We explain that how channel behaviour can be modelled using Markov Chain. Then, a power-adaptive communication protocol for WBANs is developed in which each sensor node can self-learn its channel and dynamically adjust its transmission power. We evaluate our scheme through implementing the idea using the TelosB motes. The results demonstrate that our scheme can self-learn the channel behaviours, and reduce energy consumption and interference.**

I. Introduction

Recent progress in designing tiny wireless sensors has enabled the development of Wireless Body Area Networks (WBAN). A WBAN is composed of a few to tens of miniaturized sensors attached to or implanted in the body parts. Each sensor is in charge of measuring and reporting body parameters to a gateway that is connected to a monitoring center. WBAN has been standardized in IEEE 802.15.6 [1] as an appealing technology for a wide range of applications from health monitoring to athlete training and entertainment. Tiny WBAN sensors suffer from severe resource limitations such as battery lifetime. Moreover, WBANs usually operate in a dense social area like hospitals where a WBAN may frequently encounter other WBANs, thereby producing unwanted interference. The topology of a WBAN can also be changed over time due to posture changes and mobility, which causes very unstable channels because of frequent bodily occlusions.

Due to the WBAN's channel instability, fixed power communication protocols cannot achieve high performance in terms of energy efficiency, interference mitigation, and communication reliability because: (a) a fixed-low transmission power can save energy and reduce interference but possibly produce very poor communication reliability; and (b) a fixed-high transmission power improves communication reliability at the cost of more energy consumption and more significant interference. Accordingly, a power-adaptive communication protocol for WBANs is required. To justify the necessity of such an adaptive communication protocol, we have carried out a set of experiments using the TelosB hardware platform. The CC2420 radio chip in this platform has 31 different transmission power levels. In our setup, a sensor mote is attached to the wrist of a subject and can directly communicate with a gateway attached to the chest. During the experiment, the subject stays in five postures of a gait cycle of walking as depicted in Fig. 1. In

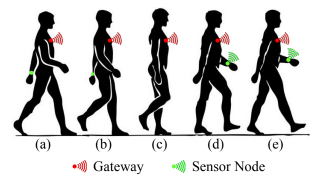

Figure 1: Network setup and postures.

Table I: PDR of Different Power Levels in Different Positions
P: power level; T: transmission range ; I: current usage

P	T (m)	I (mA)	Packet Delivery Rate (PDR)				
			(a)	**(b)**	**(c)**	**(d)**	**(e)**
1	1.2	7.6	0%	0%	0%	63.6%	84.3%
2	1.5	8.1	0%	7.1%	17.3%	88.3%	96.1%
3	35.5	8.5	92%	96.8%	95%	99.5%	99.3%
4	40.5	8.85	96.3%	99.2%	97.4%	≈100%	≈100%
5	44.5	9.2	96.6%	99.4%	97.4%	≈100%	≈100%
6	50.2	9.55	96.7%	99.4%	97.4%	≈100%	≈100%
7	> 50	9.9	99.2%	99.4%	98.7%	≈100%	≈100%

each posture, the sensor mote transmits 1000 packets to the gateway for each power level from level 1 to level 7.

Table I shows the measurements on maximum transmission range (T), current usage (I), and average Packet Delivery Rate (PDR) under each posture for the first seven low transmission power levels. The maximum transmission range is defined as the distance within which the signal-to-noise-ratio (SNR) is high enough to guarantee at least 90% of successful packet delivery. The current usage per each power level is calculated based on the data in the CC2420 data sheet [6]. According to the results in Table I, we have the following **two major observations**: (1) *power levels 1 and 2 are ideal for WBANs in terms of interference mitigation and energy efficiency.* However, they cannot provide reliable communication when the channel is blocked. (2) *power levels 3 and 4 achieve very good communication reliability for all postures.* Hence, it is not necessary to use even higher transmission powers that will consume more energy and cause more interference. However, the transmission ranges of power level 3 and 4 are much larger than those at power levels 1 and 2 and should be used as less as possible to avoid interference.

Several adaptive communication protocols have been designed for WBANs. DPPI [4] is an adaptive communication protocol which assumes a linear relationship between power level and channel quality. In DPPI, if the transmitted packet is received at the gateway, it replies back with an ACK packet including the RSSI (Received Signal Strength Indicator) of the received packet. Then, the sensor node adjusts its transmission power according to the RSSI of its last transmission. Experio [3] is another adaptive method designed for WBANs which benefits accelerometers to extract the channel pattern during periodic movements (e.g. walking). It transmits the packets opportunistically and in a bursty fashion when the channel is expected to be good.

Although the channel quality of WBANs is unstable, our experiments reveal a strong spatio-temporal dependency between the quality of consecutive channel samples. Motivated by this, we develop a power-adaptive communication protocol for WBANs, in which each sensor node can self-learn its channel and dynamically adjust its transmission power. In comparison with the existing schemes, the major contributions of our work are as follows:

- We characterize WBAN's channel behaviour and use the Markov chain model to estimate the channel quality.
- We develop a power-adaptive communication protocol in which each sensor can adjust its transmission power at a per-packet level to cope with channel dynamics.
- We evaluate the performance of the proposed communication protocol through experiments on TelosB sensor motes. The results reveal a significant reduction in energy consumption and interference range.

The rest of the paper is organized as follows. Section 2 presents the analysis on channel burstiness. The power-adaptive communication protocol is presented in Section 3. Section 4 validates the idea, and Section 5 concludes the paper.

II. Channel Characterizing and Modeling

Assume that time is slotted and one channel sample is generated in each time slot. We consider the channel samples as a discrete-time time series $X = \{x_t\}_{t=1}^{n}$ where n is the number of samples. Each sample has a value in $\Omega = \{0, 1, 2, \dots\}$ representing the channel state or the channel quality level. We group the samples in the form of *i-run-lengths* $\{i_r^c\}_{r=1}^{n}$, where i_r^c represents the r^{th} *run-length* with the length of c ($c \in \{1, 2, 3, \dots, n\}$) consecutive samples in state i. For example, the sample set $\{11112211221122333\dots\}$ can be represented by a set of run-lengths: $\{1_1^4, 2_1^2, 1_1^2, 2_2^2, 1_2^2, 2_3^2, 3_1^3, \dots\}$. This classification of channel samples gives a high-level view of channel behaviour.

To analyse the channel burstiness more accurately we carried out experiments to collect channel samples in both static postures (e.g. standing, sitting, and driving), and dynamic postures (e.g. walking and running). For the sake of simplicity, we consider only two channel states 0 and 1, for good and bad channel quality, respectively. If the gateway receives the channel sample x_t, we record the channel in good state in slot t; otherwise, the channel is recorded in the bad state. Analysis of the collected channel samples reveals burstiness in WBAN's channel which means if the current channel state is good, the channel state in the next slot is most probably good, though this probability depends on burst length.

Gilbert Elliot (GE) model [2], is a simple two state Markov chain which has been widely used for modeling burst error patterns of communication links. It has two states G (for good) and B (for bad). Since GE model is memoryless, it cannot accurately characterise the burst length. The Extended

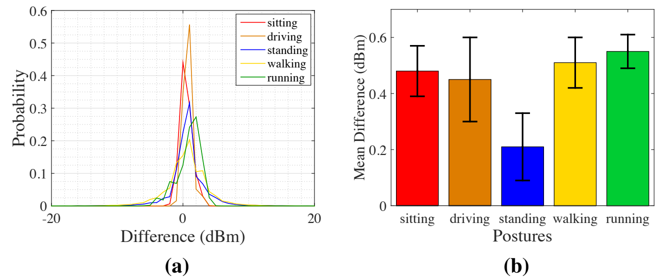

Figure 2: (a) Probability distribution of difference of RSSI at sensor node and gateway (b) Mean and standard deviation of differences.

GE model (EGE) was proposed in [5] to remember the channel history. Similar to GE, EGE model has two general states: G and B, each of which has some internal sub-states. Therefore, EGE has two types of transitions: intra-transition when the current channel state is similar to the previous state, and inter-transition when the current state is different from the previous state. Using internal states, EGE recognizes burst length and can accurately predict the channel behaviour.

III. Power-adaptive Communication Protocol

Our proposed method is to dynamically control the transmission power at a per-transmission level based on channel prediction. The challenges are how to estimate the channel and how to decide which power level is the best. Our key idea is to explore channel symmetry and RSSI-based thresholding.

A. Validation on Channel Symmetry

We carried out a set of experiments to justify the symmetry of the wireless channels in WBANs. In this set of experiments, the gateway and the sensor node periodically exchange packets. The sensor node measures the RSSI for each packet transmitted by the gateway and immediately replies to the gateway by including the measured RSSI in its packet. On the other hand, the gateway measures the RSSI for each packet transmitted by the sensor node. Hence, the gateway can get the RSSIs for the links in both directions. The experiment was repeated for five different daily postures including sitting, driving, standing, walking, and running, with each one lasting for five minutes.

Fig. 2(a) shows the probability distribution of the difference between the measured RSSIs at the sensor node and the gateway for power level 4. It can be seen that the difference on RSSIs from and to the gateway has a normal distribution in all postures. The mean of differences on RSSIs between measured samples is depicted in Fig. 2(b), as well as their standard deviation. Since the mean and the standard deviation of each distribution is close to 0, it can be concluded that the channel under power level 4 is symmetric. We repeated the experiment for other power levels and got the same conclusion.

B. Channel State Model and Communication Protocol

As discussed in Section I, the lowest four power levels of CC2420 radio chip are enough for reliable communication in WBANs. Therefore, we partitioned the channel quality into four states so that each state i ($i \in \{1, 2, 3, 4\}$) represents a channel quality for which power level i is the lowest level to achieve high communication reliability. Since RSSI measurements can show the channel quality variation, each channel state i is defined as a sub-range of RSSI in which power level i is the lowest reliable level for communication. To find the boundaries of corresponding RSSI range per each channel state i, four rounds of experiments are done. Assuming time is slotted, in each slot of round i, the sensor node transmits a packet using power level i. Then, the gateway sends another packet with power level 4 back to the sensor node whether the sensor node's packet is received or lost. This packet includes a field to show the delivery status of the sensor node's packet. When the sensor node receives the packet, the RSSI is measured, and the mentioned field is checked. Through counting the number of delivered packets, the reliability of communication with power level i per each level of RSSI is calculated. RSSI boundaries for a state i are selected so that, 99% PDR is guaranteed using power level i.

Algorithm 1: Proposed ATPS

```
Input  : channel model properties at time slot t − 1
1  p ← generate a packet;
2  retrans_count ← 0;
3  channel(t) ← estimated channel state at current time t;
4  do
5      i ← channel(t); /* select power level        */
6      send(p, i); /* send with power level i       */
7      if ACK is received then
8          rssi ← RSSI(ACK);
9          channel(t) ← real state determined by rssi;
10         update channel model properties;
11         break;
12     end
13     retrans_count + +
14     update model properties;
15     channel(t) ←estimated channel state at time t;
16 while retrans_count < retrans_threshold;
```

Algorithm 1 shows the procedure of the proposed ATPS. When a packet is generated, the sensor node estimates the current channel state using EGE model, and selects the corresponding power level (line 3). Once the channel state is estimated, and the power level is selected, the packet is transmitted (line 6). Since the time difference between sending a packet and receiving its ACK packet is short, it is reasonable to assume that the channel does not change during a time slot. Due to the channel symmetry, the sensor node finds the real current channel state using the measured RSSI of the received ACK. According to the EGE model, the transition probabilities are updated for future channel estimation. In case the ACK packet is not received, the sensor node finds the channel quality is lower than its estimation. Thus, it makes another estimation among the states related to the lower channel quality. If retransmission is enabled, the sensor node repeats all steps mentioned above.

IV. Experimental Evaluation

In this section, we evaluate the performance of our proposed scheme in comparison with existing protocols regarding energy usage, interference range, and communication reliability.

A. Experiment Setup

We use the setup described in Section I. The sensor node communicates with the gateway in a constant packet rate according to a predefined TDMA schedule. Data packet size is set to 41 bytes. In addition to ATPS (which uses EGE with 50 internal states per each general state), Experio [3] and two non-adaptive protocols with fixed low power (FLP) and fixed high power (FHP) level are also implemented in TinyOS 2.2. FLP transmits all packets with power level 1, whereas FHP communicates with power level 4. To provide a lower bound on the minimum possible interference and energy usage, the optimal scenario (where the best power level is computed offline) is considered as well.

All experiments have been conducted under two packet rates: 1 packet per 10 seconds for low packet rate applications (e.g. monitoring blood pressure), and 20 packets per second for high packet rate applications (e.g. EMG monitoring systems). In low packet rate scenario, the sensor node position and accordingly, the channel quality might be changed a couple of times during the period between two consecutive transmissions. Since the updating period of EGE's transition matrix is proportional to the packet rate, the channel quality prediction is quite erroneous in low packet rate applications. Hence, we modify the proposed communication protocol by adding a self-triggered training period. After detecting a couple of channel mispredictions, the training period is triggered and the gateway transmits 100 tiny 11 bytes beacon packets to the sensor node at the rate of 20 packets per second. Using this as a learning sequence, the sensor node updates the model properties.

The experiments are performed by three subjects, and the results are averaged among ten trials. The subjects are asked to follow four body postures (including sitting with folded hand, standing upright, walking, and running) with each posture lasts for 30 minutes. All experiments are repeated with disabled and enabled MAC sub-layer retransmission. If retransmission is enabled, a lost packet is allowed to be retransmitted up to 15 and 3 times, in low and high packet rate, respectively.

B. Comparing ATPS with other protocols

Table II presents the packet loss rate and energy usage of different communication protocols in various scenarios.

1) Scenarios with disabled retransmission: In these scenarios, packet rate does not influence the performance of FLP, FHP, and optimal scenario. FHP has the lowest packet loss (utmost 2.6% in standing). In contrast, FLP cannot deliver even one packet when the channel is blocked though, its energy usage is the lowest. Besides, the optimal solution is as reliable as FHP, but uses less energy. In static postures, Experio behaves like FHP, but in walking and running, it schedules the packets to be transmitted once line-of-sight is

Table II: Average per packet energy consumption / packet loss rate of different protocols under various scenarios

Protocol	Packet Rate	Average Energy Consumption (μJ) / Packet Loss (%)							
		Retransmission Disabled				Retransmission Enabled			
		Sitting	Standing	Walking	Running	Sitting	Standing	Walking	Running
FLP	0.1	29.91/1.8	29.91/100	29.91/45	29.91/74.2	30.44/0	478.62/100	70.30/0	95.72/0
FHP	0.1	34.83/0	34.83/2.6	34.83/0.4	34.83/0.6	34.83/0	35.74/0	34.97/0	35.04/0
Experio	0.1	34.83/0	34.83/2.6	341.52/53	348.34/51.1	34.83/0	35.74/0	358.93/0	365.23/0
ATPS (EGE)	0.1	29.96/1.4	36.08/2.9	44.39/4.2	51.74/11.1	30.68/0	37.68/0	45.86/0	52.18/0
Optimal	0.1	29.95/0	33.18/2.6	31.65/0.4	32.48/0.6	29.95/0	33.65/0	31.78/0	32.61/0
FLP	20	29.91/1.8	29.91/100	29.91/53.2	29.91/72.6	30.44/0	119.66/100	45.80/42	51.63/70.3
FHP	20	34.83/0	34.83/2.7	34.83/0.4	34.83/0.6	34.83/0	35.74/0	34.52/0	35.04/0
Experio	20	34.83/0	34.83/2.7	32.37/3	33.19/2.4	34.83/0	35.74/0	34.52/0	33.89/0
ATPS (EGE)	20	29.95/0.6	33.37/2.8	31.65/5.5	32.44/5.7	30.14/0	34.03/0	33.40/0	34.56/0
Optimal	20	29.95/0	33.18/2.7	31.65/0.4	32.48/0.6	29.95/0	33.65/0	31.78/0	32.57/0

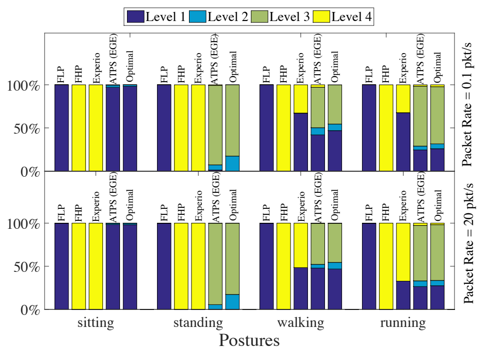

Figure 3: Distribution of usage of power levels in various protocols.

available. This scheduling decreases energy usage and delivers most of the packets when the packet rate is high. But, in low packet rate, since fewer ACK packets (i.e. feedbacks) are received, channel prediction is more erroneous that causes more than 50% packets loss (consequently requesting more learning packets) and about $341\mu J$ energy usage.

In low data rate scenario, the per-packet energy consumption of ATPS is slightly higher than that for FHP. This increase in energy usage is caused by the requests on learning sequence, especially for dynamic postures. However, it saves much more energy in comparison with Experio (around 87%). In high data rate scenario, the performance of ATPS is close to the optimal solution, since the channel model can get timely channel feedbacks and increase the accuracy of channel prediction. Although ATPS does not perform much better than FHP in terms of energy consumption during walking and running, it produces much less interference as it adaptively controls the transmission power according to the predicted channel quality. Fig. 3 shows the distribution of the power levels used in discussed protocols. It can be seen that ATPS transmits more than 97.4% of the packets with power level 1, when the subject is sitting, only 0.6% less than that of optimal scenario. It also transmits about 44% and 25% of the packets using power level 1 in walking and running, respectively. This is very close to the behaviour of the optimal solution which sends 47% and 26% of the packets with power level 1 in the same postures.

2) Scenarios with enabled retransmission: All protocols except FLP can achieve 100% reliability when retransmission is permitted. In sitting, FLP delivers all packets but, none of the retransmitted packets in standing is received at the gateway, regardless of packet rate. In walking and running, the channel is not blocked for a long time. Hence, FLP can finally deliver a lost packet. In the high packet rate scenario, the energy usage of FHP is not increased too much, as its loss rate is limited. On the other side, FLP has to retransmit many lost packets. Hence, its energy usage is raised significantly. In low packet rate, Experio is imposed about $17\mu J$ more energy usage in both walking and running, which is about 8 times in walking and 7 times in running more than that of ATPS. The distribution of the usage of different power levels for the high data rate scenario has the same trend as that for the low data rate scenario. It can be concluded that ATPS is much more energy efficient compared to Experio and FLP. In comparison with FHP, it consumes slightly more energy in the low packet rate scenario but produces much less interference than FHP.

V. Conclusion

The paper discusses the attributes of channel variation in WBANs. Based on the channel prediction using Markov chain, we developed ATPS, an adaptive transmission power selection for low-energy and low-interference communication in WBANs. The experimental results in a wide variety of scenarios demonstrate that our scheme can self-adapt to channel burstiness patterns and choose the lowest reliable power level to reduce energy consumption and interference.

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