LPA: Learning-based Power Aware Communication Protocol in WBANs

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

***Abstract*—Radio links in wireless body area networks (WBAN) experience highly time-varying attenuation because of topology instability. On the other hand, real-time, reliable, energy efficient and interference-aware communication protocol is the most important requirements of many WBAN applications. Since the channels quality is not stable, there is no any fixed optimal power level which meets all the requirements. In this paper, an adaptive Learning-based Power Aware (LPA) communication protocol is proposed that is capable of selecting the appropriate transmission power level based on the channel status. Since LPA is based on learning automata, it is a feedback based protocol in which the transmission power level is increased when it finds the channel is bad, and decreased as soon as it finds the channel is good. The performance of LPA is evaluated experimentally in five different postures and under three different data rates. The results are compared with communication protocols using fixed transmission powers under different scenarios with different data rates. The experimental results show LPA can save up to 55% of the energy consumed by the communication protocol using fixed high transmission power while the reliability of the communication is the same when the Medium Access Control (MAC) sublayer retransmission is enabled.**

I. Introduction

Fast advancements of short-range wireless technologies have enabled the development and deployment of ubiquitous wearable networks that consist of a few or tens of miniaturized sensors. This special kind of wireless sensor network called Wireless Body Area Network (WBAN), is standardized in IEEE 802.15.6 [1] and covers a wide range of different applications from ambulatory health care and assisted living systems to entertainments, sports and even military applications [2]. In all these applications, each sensor node is capable of measuring a parameter and transmitting it to the gateway which is in charge of connecting the WBAN to the monitoring center or other networks using the Internet or existing fixed structures like cellular networks.

Although the network size of a WBAN depends on its application, in [3] it is stated that each WBAN should be able to support up to 256 sensor nodes. Since the network area is limited to the human body, WBANs are highly dense. Moreover, WBANs usually operate in the dense social environments like hospitals, clinics, and nursing homes, and frequently encounter each other or other WSNs around the network area. Hence, short-range low power communication protocols are necessary to avoid inter- and intra-network interferences. On the other hand, similar to other kinds of WSNs, battery life and energy consumption in WBANs are very important especially in health care systems where in-body sensors are not accessible for many years to change or recharge the batteries. All these constraints make low power communication protocols inevitable in WBANs.

Several energy efficient low power communication approaches have been proposed. However, they are based on energy efficient routing and multi-hop communications [4], optimal nodes placement [5]–[7] and opportunistic communications [8]. Optimal node placement in WBAN, although may improve network lifetime, is not very applicable because node positions usually depend on the specific application. Also, the topology of WBAN varies because of the body postural movements. On the other hand, multi-hop routing protocols usually impose lots of routing messages to the network and opportunistic communication protocols usually have to work under special scenarios like periodic movements.

In this paper, we consider a one-hop WBAN that consists of a few sensors communicating directly with a gateway attached to the chest. In this scenario, each sensor measures a parameter and sends the measured value to the gateway periodically. Since the body posture varies with time, the channel quality and distance between the sensor node and the gateway vary. Under such variations, we aim to design a power aware communication protocol to adjust the transmission power level adaptively in order to reduce power usage and interference range. Compared to the previous works, our contributions are summarized as follows:

- We propose LPA, a lightweight learning-based power aware communication protocol, to intelligently select the lowest possible power level based on the channel quality. The lowest possible level of transmission power is the level with which the communication reliability is high enough and other lower levels cannot supply acceptable communication reliability. LPA is interactive and based on the ACK packets are received at the sensor, it adjusts its transmission power. LPA is highly reliable, real time, and simple to implement which does not impose extra message passing or remarkable processing overhead to the network.
- We validate the performance of our proposed protocol through experiments under three different data rates in five different common scenarios including sitting, driving, standing, walking and running to cover most of the daily activities for different applications. Our experiments show remarkable energy saving is achieved by LPA and even interference range is decreased to its minimum in two

scenarios (sitting and driving) while in other scenarios interference range is reduced.

The rest of the paper is organized as follows. Section II discusses the related works. Section III explains our motivation. Our proposed protocol LPA is described in Section IV. The experimental results are presented and discussed in Section V. Finally Section VI concludes the paper.

II. Related Works

In this section, we first give an overview of other power aware protocols designed for WBANs, then explain in which way LPA differs from existing works. Existing power aware communication protocols in WBANs can be categorized into two types: *opportunistic* and *probabilistic*. Opportunistic communication protocols try to exploit the connectivity pattern of the links to estimate the channel and transmit a packet when the link is expected to be connected. ExPerio [8] is a good example of this type of protocols which tries to detect the opportunities in periodic movements through mapping the Received Signal Strength Indicator (RSSI) measurements and inertial data. ExPerio needs lots of information about the body postural movements and the current trend of body parts. Hence, it imposes remarkable message passing and processing overhead to the network. Besides, in ExPerio high communication rate between the sensor node and the gateway is needed because the sensor node needs continues monitoring of the body postural movements to exploit periodicity.

In probabilistic communication protocols, each sensor node sets a communication probability with other nodes in the networks based on its communication history. Then whenever a sensor node has a packet ready to send, it communicates with the gateway directly or selects a relay node with a higher probability of successful communication when the gateway is not accessible. Although the processing overhead of this type of protocols is usually low, its performance highly depends on the network size. PRPLC [9], DVRPLC [10] and BAPR [11] are examples of probabilistic protocols.

Our proposed LPA is a probabilistic protocol which tries to adjust its transmission power level opportunistically. LPA does not need any extra information about body postural movements or network topology. Moreover, the performance of LPA does not directly depend on the data rate, though extremely low data rate plus rapid fluctuation of channel quality may decrease its performance. Last but not least, the performance of LPA does not depend on the network size because power level adjustment is done locally at each sensor node and it could be easily extended to a multi-hop communication.

III. Motivation

Like other types of wireless sensor networks, WBANs suffer from various constraints including limited energy budget, unreliable wireless communication channels, and interference from nearby sensors and WiFi devices. Low power communication in WBANs is preferred from various points of view:

(1) Interference: WBANs may encounter each other, as shown in Figure 1, so inter-network interference becomes more severe if the sensors communicate with high transmission power. In [1] it states that transmission range should be lower than 3 meters when up to 10 WBANs are located in a space of $6\,m^3$. Since the distance between the sensors in a WBAN is usually lower than a few dozens of centimetres intra-network interference is another challenge. Moreover, WBANs may produce noise for other WSNs like house monitoring systems when the transmission power is high and consequently the interference range is large.

(2) Energy consumption: Although energy efficiency is an important metric for almost all wireless devices, it is more critical in WBANs. Battery replacement in WBANs is not possible for those implanted sensors which are expected to work for many years. Another constraint is battery size. For many applications, the sensors attached to the body are required to be small, which limits the battery size and its power capacity. To maximise the lifetime of the sensor nodes, the transmission power should be as low as possible under the condition of reliable communications.

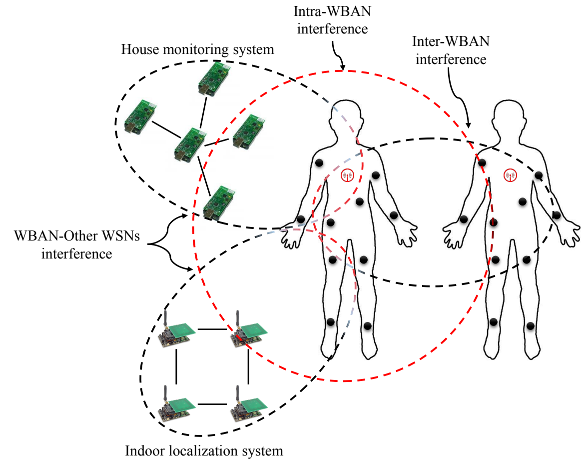


Figure 1. Different types of interference in WBANs

Despite the fact that low power communication is desirable in WBANs, it is not always possible. Since a human body may experience different postures even in a short period of time (e.g. sitting, standing, walking, etc), the network topology is usually changing over time. This instability in network topology and sensor position can create significant fluctuations in the quality of wireless channels due to frequent blockage and variable absorptions of the radio propagation energy by body parts. If the sensor nodes always communicate with low transmission power, then frequent network partitioning and consequently significant packet loss would be inevitable.

To identify the relationship between transmission power, body postures, packet error rate (PER) and interference range, we have carried out a set of experiments using the MTM-CM4000 sensor motes. Each sensor mote consists of an MSP430 micro-controller and a CC2420 radio chip which works in a frequency band of 2.4GHz. The CC2420 radio chip supports 32 levels of transmission power ranging from 1

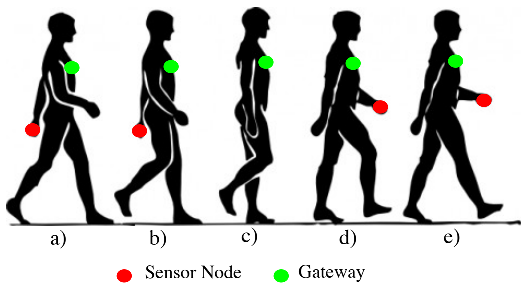


Figure 2. Unstable topology in WBAN during walking. Line-of-sight between the sensor node and the gateway is interrupted by body parts in a), b) and c).

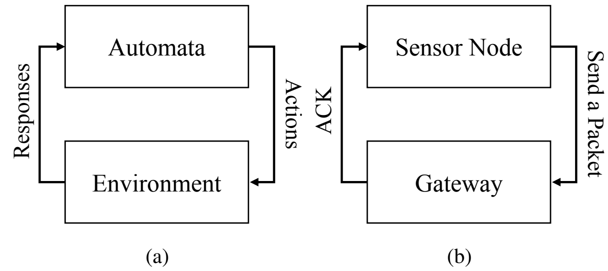


Figure 3. Feedback loop between (a) automata and environment, (b) the sensor node and the gateway.

to 32. A human subject equipped with two sensors (a sensor node at the wrist and a gateway at the chest) stayed in five common postures of walking, as depicted in Figure 2. The data rate was set to 3200 bps. Each posture was repeated for 12 different transmission powers as listed in Table I and PER in each power level and posture was averaged among 20 trials.

The most important observation from Table I is that the lower transmission power levels like level 1 and 2 have much lower energy consumption and shorter transmission range which is ideal for energy saving and interference avoidance, but communication reliability of these levels are extremely low. On the other hand, higher transmission power levels decrease packet loss remarkably and guarantee reliable communications, but increase energy consumption and interference range significantly. For example, packet loss of level 7 is almost 1%, but its energy consumption and interference range is 60 and 40 times greater than that of the level 1 respectively.

Though we only investigated the packet loss rates of five walking postures under different transmission power levels, our observations can apply to other postures like standing or sitting behind the desk for a relatively long time. For example, when people are standing, they may put their hand in their pocket. Since the line-of-sight (LoS) between the sensor node and the gateway would not be available, packets are lost if a low transmission power is used. On the other hand, if someone folds his/her arms, not only the LoS would be available, but also the distance between the sensor node and the gateway is decreased to a few centimeters. In such a case, using the lowest transmission power level would stop wasting energy and reduce interference. Consequently, we know that the sensor node should be smart enough to dynamically adjust the transmission power level according to different postures.

IV. Learning Based Communication Protocol in WBAN

In this section, we propose an adaptive communication protocol, LPA, based on learning automata.

A. Learning Automata

Learning Automata (LA) [12] is an adaptive online learning method which tries to discover the attributes of the environment through trial and error. In LA, the automata know nothing about the relationship between its action and the response of the environment but tries to discover it through a feedback loop, as shown in Figure 3a. A learning automata can be defined using a quintuple $\{A, B, S, F, G\}$, where

- $A = \{a_1, a_2, \cdots, a_n\}$ is a finite set of actions or outputs of the automata. The action of the automata at any time t, denoted by $a(t)$, is a member of A.
- $B = \{b_1, b_2, \cdots, b_r\}$ is a finite or infinite set of responses. The response of the environment at any time t is denoted by $b(t)$ which is a member of B.
- $S = \{s_1, s_2, \cdots, s_m\}$ is a finite set of internal states. Let $P_{a_i}(t)$ denote the probability that the learning automata takes action a_i at time t (i.e. $P_{a_i}(t) = Prob[a(t) = a_i]$). The state at any time t, denoted by $s(t)$ ($s(t) \in S$), is represented as below:

$$s(t) = \{P_{a_1}(t), P_{a_2}(t), \cdots, P_{a_n}(t)\} \quad (1)$$

  where $\sum_{i=1}^{n} P_{a_i}(t) = 1$.
- F is a function that maps the current state $s(t)$ to a new state $s(t+1)$ based on the response from the environment: $s(t+1) = F(s(t), b(t))$.
- G is a function that determines the next action based on the current state: $a(t+1) = G(s(t))$.

If either F or G are stochastic, it is called a stochastic learning automata and suitable to stochastic environments. If G is stochastic, the action with higher probability has more chance to be selected. As mentioned before, the automata work based on trial and error. If an action a_i is selected at time t, the probabilities for all actions at time $t+1$ should be updated based on a learning function and the response of the environment. Below is an example of a lightweight learning automata which uses a linear reward-penalty scheme (denoted L_{R-P}):

- If the response is good,

$$P_{a_i}(t+1) = P_{a_i}(t) + \alpha_i \times \big(1 - P_{a_i}(t)\big), \quad (2)$$

$$P_{a_j}(t+1) = (1-\alpha_i) \times P_{a_j}(t), \forall a_j \in A \text{ and } a_j \neq a_i \quad (3)$$

- If the response is bad,

$$P_{a_i}(t+1) = (1 - \beta_i) \times P_{a_i}(t) \quad (4)$$

$$P_{a_j}(t) = \frac{\beta_i}{n-1} + (1-\beta_i) \times P_{a_j}(t), \forall a_j \in A \text{ and } a_j \neq a_i \quad (5)$$

Table I
PACKET LOSS RATE UNDER DIFFERENT TRANSMISSION POWER LEVELS IN DIFFERENT POSTURES

Power (Level)	Transmission range (m)		Energy usage (mW)	Packet loss in different positions				
	PER $< 10\%$	PER $< 50\%$		(a)	(b)	(c)	(d)	(e)
1	1.2	1.25	0.5×10^{-3}	100%	100%	100%	36.4 %	15.7%
2	1.5	1.55	1.35×10^{-3}	100%	92.9%	82.7 %	11.71 %	3.91%
3	35.5	35.8	3.16×10^{-3}	8%	3.2%	5%	0.5 %	0.7%
4	40.5	40.75	6.6×10^{-3}	3.7%	0.8%	2.6%	≈0 %	≈0%
5	44.5	44.75	12×10^{-3}	3.4%	0.6%	2.6%	≈0 %	≈0%
6	50.2	50.3	20.4×10^{-3}	3.3%	0.6%	2.6%	≈0 %	≈0%
7	> 50	> 50	31.6×10^{-3}	0.85%	0.6%	1.3%	≈0 %	≈0%
8	> 50	> 50	45.7×10^{-3}	0.6%	0.6%	1%	≈0 %	≈0%
9	> 50	> 50	61.7×10^{-3}	0.5%	0.6%	0.8%	≈0 %	≈0%
10	> 50	> 50	79.4×10^{-3}	0.5%	0.5%	0.7%	≈0 %	≈0%
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
16	> 75	> 75	0.2	≈0%	≈0%	≈0%	≈0 %	≈0%
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
32	> 100	> 100	1	≈0%	≈0%	≈0%	≈0 %	≈0%

where α_i and β_i are reward and penalty factors for action a_i and are within $[0, 1]$. As explained in [12] and can be seen in Equations (2) and (3), when the response is good, probability of the selected action is increased as much as $\alpha_i\big(1 - P_{a_i}(t)\big)$ and the selection probability of other $n-1$ actions is decreased by $\alpha_i P_{a_j}$. Since α_i is less than one it guarantees P_{a_i} remains smaller than one. Besides, since $\alpha_i\big(1 - P_{a_i}(t)\big)$ equals to $\sum_{j=1,j\neq i}^{j=n} \alpha_i P_{a_j}$, the sum of all selection probabilities remains 1 after updating the probabilities. On the other hand, when the response is bad, the probability of the selected action is decreased by $\beta_i P_{a_i}$ as shown in Equation (4). The selection probabilities of other actions vary by $(\frac{\beta_i}{n-1} - \beta_i P_{a_j})$.

The reward and penalty factors, α_i and β_i, are the most important components as they have a large impact on the performance of the learning automata. The design of these two factors should take into account of the features of the application scenario and the problem to be solved. In the next subsection, we propose our reward and penalty factors to control the behaviours of LA, e.g. the transmission power, based on the requirements of WBANs.

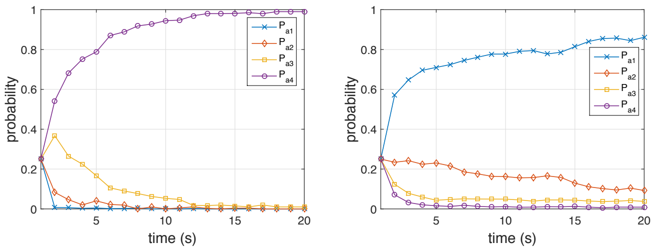
B. LPA Proposed Protocol

As mentioned before, we assume that a WBAN is composed of one gateway and multiple sensor nodes. All sensor nodes communicate with the gateway according to a predefined TDMA schedule. Each sensor node has n transmission power levels (level 1 is the lowest and level n is the highest). Each node can dynamically adjust its transmission power at per-packet level. To enable power-aware communication in an unstable topology, each sensor node should adaptively control its transmission power with the expectation that packets can be successfully received using the lowest possible transmission power to reduce energy consumption and interference. To do this, each node should be able to estimate the channel quality (e.g., through feedbacks from the gateway) and then increases the transmission power whenever the channel quality is bad or decreases transmission power as soon as the channel quality becomes good. To have such an estimation of channel quality, a continuous interaction between the sensor node and the gateway is required. As an easy solution, the sensor node can request ACK packet for all or some of its packets to check if the channel quality is good or bad. At the sensor node side, a timer is set up for each packet transmission. If the sensor successfully receives the ACK before the timer is expired, the channel is interpreted as good; otherwise, the channel is bad.

Since both the above adaptive power control scheme and LA are feedback based, we can map this adaptive power control scheme onto the LA model. Each sensor node runs a learning automata and interacts with the environment (channel and the gateway) via a feedback loop as shown in Figure 3b. Based on the response from the environment (good/bad channel quality), the sensor node selects the most appropriate action (i.e., the transmission power level). Since each sensor node has n transmission power levels, the automata has n actions, i.e., $|A| = n$.

C. Power- and Reliability-aware Reward & Penalty Functions

In LPA, each action is selected to get more rewards and fewer penalties in a greedy way. If we set equal rewards and equal penalties for all actions ($\alpha_i = \alpha_j$ and $\beta_i = \beta_j$, $\forall a_i, a_j \in A$), LPA tends to select the highest power level because the communication reliability achieved using higher transmission power is larger than that achieved using lower transmission power levels. In other words, LPA tends to select the highest level because the probability of successful communication and getting reward with it is much higher than



(a) (b)

Figure 4. LPA behaviour a) equal rewards and penalties, b) energy-aware rewards and penalties.

other choices. To show the result of using equal rewards and equal penalties for LPA actions, an experiment was done using the MTM-CM4000 sensor motes with the CC2420 radio chip. In this experiment, we consider the first four transmission power levels of the CC2420 radio chip, (i.e. $n = 4$) because the results in Table I show the communication reliability of level 4 is high enough even when the LoS between the sensor node and the gateway is blocked. Other lower levels (level 1 to level 3) are used to reduce energy consumption and interference when the channel is good and low power communication is possible. The human subject wears two sensors in the way depicted in Figure 2 and stands like position (e) of the same figure for 20 seconds. The sensor node continuously sends the data packets to the gateway. At the beginning, the probability of selecting each of these four power levels is set to 0.25. According to Table I, the communication reliabilities with these four power levels in this posture are $84.3\%, 96.09\%, 99.3\%$, and 100%, respectively. As shown in Figure 4a, after a few iterations of the LPA, P_{a_4} reaches to 1 and the selection probabilities of other actions reach to zero.

To reduce energy consumption and interference, we should encourage the LPA to select lower levels of transmission power. To achieve this, we redefine the reward and penalty factors for each action a_i as follows:

$$\alpha_i \propto \frac{E_1}{E_i}, \quad \beta_i = 1 - \alpha_i \tag{6}$$

where E_i is the energy consumption at power level i. The reward factor α_i ensures that higher power levels have lower rewards, whereas the penalty factor β_i guarantees that higher power levels have larger penalties.

To validate the new reward and penalty factors, the previous experiment was repeated. As shown in Figure 4b, unlike the previous experiment, LPA tends to select a_1. This big change in LPA trend is only because of the redefined rewards and penalties. With these new rewards and penalties, in the LPA, one successful communication after a few unsuccessful communications with a_1 is preferred than the reliable communications with a_4. In other words, since the energy consumption of a_1 is much lower than other actions, LPA would like to tolerate some packet loss to save energy.

Since different applications of WBANs require different quality of services, a general purpose reward and penalty factors should consider both the reliability and power of communication. The following equation gives an enhanced version of our reward factor, that takes into account of both communication reliability and transmission power level.

$$\alpha_i = \omega_i \times \frac{E_1 \times R_i}{E_i}, \quad i = 1, 2, 3, \ldots, n \tag{7}$$

where $\omega_i \in (0, \frac{E_i}{E_1 \times R_i})$ is a weighting factor and R_i is the communication reliability achieved by selecting action a_i. The upper bound $\frac{E_i}{E_1 \times R_i}$ on ω_i guarantees that α_i does not exceed 1. It can be seen that α_i is proportional to the communication reliability and inversely proportional to energy consumption. This ensures that (a) the higher reliability the larger the reward, and (b) the higher the transmission power the smaller the reward. By properly adjusting the weighting factor, we can explore the tradeoff between communication reliability and energy consumption. For example, if we want to have low power communications, we could adjust the weighting factor for each action to ensure that $\alpha_i > \alpha_j$, $\forall i < j$. On the other hand, if we want to emphasize reliable communications, the weighting factor can be adjusted to guarantee that $\alpha_i < \alpha_j$, $\forall i < j$.

In the LA model given in Section IV-A, if the automata get a positive (or negative) response for action a_i, it updates the selection probability of all other actions as explained in Equations (2), (3), (4) and (5). This is a good way when there is no correlation between different actions. However, in WBANs there are correlations between taking different transmission powers. For example, when the sensor node does not receive an ACK for choosing a_i, it means all actions with lower power levels most likely get the same response. On the other hand, if the sensor node gets ACK, it most likely gets the same response using all higher power levels. To improve the performance of the LPA, we have redefined Equations (2), (3), (4) and (5) as follows:

- If the response is good

$$P_{a_i}(t+1) = P_{a_i}(t) + \alpha_i[(1 - \sum_{j=1}^{j<i} P_{a_j}) - P_{a_i}(t)] \tag{8}$$

$$P_{a_j}(t+1) = \begin{cases} P_{a_j}(t), & if(j < i) \\ (1-\alpha_i) \times P_{a_j}(t), & if(j > i) \end{cases} \tag{9}$$

- If the response is bad

$$P_{a_i}(t+1) = \begin{cases} (1-\beta_i) \times P_{a_i}(t), & if(i \neq n) \\ P_{a_i}(t), & if(i = n) \end{cases} \tag{10}$$

$$P_{a_j}(t+1) = \begin{cases} P_{a_j}(t) & if(i == n) \\ (1-\beta_i) \times P_{a_j}(t), & else\, if(j < i) \\ P_{a_j}(t) + \frac{\beta_i \sum_{k=1}^{i} P_{a_k}(t)}{n-i}, & else \end{cases} \tag{11}$$

It can be seen that, when the sensor node gets a good response, the selection probabilities for higher power levels are decreased because the selected action is reliable and there is no incentive for the LPA to select an action with a higher power level. On the other hand, the selection probabilities of all actions with lower power remain unchanged because, based on the good response to the selected action, we cannot decide whether those actions with lower power are or are not reliable. However, when the response is bad it decreases the selection probability of all lower levels because, when the communication with a power level is not reliable, the lower levels would not be reliable as well. Moreover, LPA increases the selection probability of all higher levels to increase the chance of reliable communication. But there is an exception when LPA selects action a_n. In our case, since a_n is the highest power level and a more reliable action for the sensor node is not defined, LPA does not decrease P_{a_n} when a packet loss occurs. Moreover, when a successful transmission with a_n occurs, we do not increase P_{a_n} because we cannot decrease selection probability of other lower powers as we explained.

A critical problem in the LPA happens when the channel is blocked for a relatively long time (the time depends on different factors like reward and penalty factors, learning scheme and data rate). In this situation, the selection probability of the low power levels may reach to zero after a number of unsuccessful attempts. So when the sensor node moves to a good position, the LPA does not select lower power levels because the selection probabilities of these actions reached to zero. To avoid this potential problem which usually happens in daily activities, we set a minimum selection probability for the low power levels. In this way, when the channel is blocked for a long time, the selection probabilities of these actions reach to its minimum not to zero.

V. Experimental Evaluation

In this section, we evaluate the performance of LPA under five different common scenarios to show how our proposed adaptive protocol can improve network performance. In our experiments, LPA is compared with two fixed power level communication protocols, under the same scenarios.

A. Experimental Setup

In our setup, we implement an application on a wrist-worn sensor node which communicates with the gateway on the chest with a constant packet rate. Each packet includes packet number and the current transmission power level of the sensor node. The gateway records both the number and transmission power level of the correctly received packets and then transmits the results to a laptop, where the results of the experiments are recorded and the behaviour of the communication protocols are monitored.

As explained in Section IV-C, four lowest power levels for our proposed LPA are defined to consider the impact of the adaptive communication protocol on three metrics: energy saving, interference reduction due to low power communication, and communication reliability which is the probability of successful communication. Two more communication protocols with fixed low power (FLP) and fixed high power (FHP) level are also implemented and compared. In the FLP, the sensor transmits all packets with the lowest transmission power level (level 1), while, in the FHP, the sensor communicates with the highest power level (level 4).

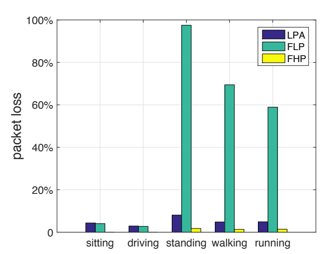
We performed 12 different experiments in total and averaged the packet loss rate and energy consumption among 10 trials. In each experiment, the subject wearing the WBAN follows the five predefined scenarios indoor, with each scenario lasted for one minute. The five scenarios are described as follows.

- **Sitting with folded hand** In this scenario, the distance between the sensor and the gateway is only a few centimeters. This scenario has been chosen to cover all those postures where the hand is very close to the chest (e.g., eating, drinking, brushing teeth, etc).
- **Driving** For many postures like writing behind a desk, the wrist is usually not very close to the chest and the distance is around dozens of centimeters but the LoS is available. Driving is a typical posture that covers the above postures. In this posture, the driver puts his/her hands on the steering wheel.
- **Standing Upright** In this posture, the thumb of the subject is parallel to the trouser so that the sensor node is very close to the side pocket of the trouser and the LoS to the gateway is completely blocked.
- **Walking** In this posture, the channel quality varies with time, so it is a good scenario to consider how LPA can adaptively change its behaviour.
- **Running** During running the channel quality varies faster than walking, so it could test the limit of the protocols.

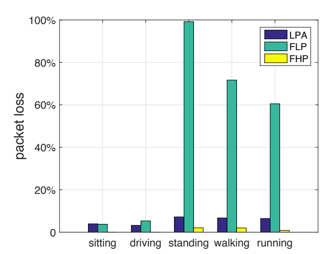
B. Experimental Results with two different data rates

Since various applications have different requirements of data rate, we performed the experiments under two different packet rates: 10 and 40 packets per second. The packet length is 20 Bytes for all the experiments and the retransmission at the Medium Access Control (MAC) sublayer is disabled so that each packet is transmitted only once at the MAC layer. As shown in Figure 5, the packet loss rates of LPA and FHP are much lower than that of the FLP in the cases of standing, walking and running, though LPA has a slightly higher packet loss rates than FHP in these scenarios.

Figure 6 shows the energy consumption of different protocols in different postures. The energy consumption is calcu-



(a)

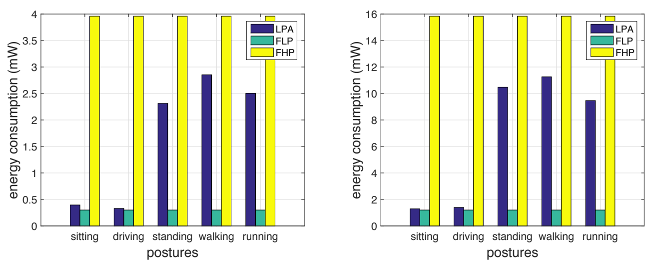


(b)

Figure 5. Packet loss rate in five different postures a) data rate = 1600 bps b) data rate = 6400 bps.

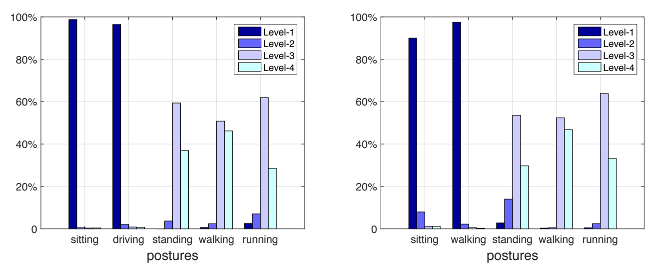
Table II
COMPARISON BETWEEN LPA AND FIXED POWER LEVEL COMMUNICATION PROTOCOLS

Protocol	**Data Rate** (bps)	**Distribution of different power levels**				**Reliability**	**Energy Consumption** (mW)
		Level 1	**Level 2**	**Level 3**	**Level 4**		
LPA	1600	38.4%	5.6%	33.3%	22.7%	94.8%	10.5
LPA	6400	40.4%	3.2%	34.6%	21.8%	94.6%	38
FLP	1600	100%	0%	0%	0%	52.9%	1.5
FLP	6400	100%	0%	0%	0%	51.75%	6
FHP	1600	0%	0%	0%	100%	99.1%	19.8
FHP	6400	0%	0%	0%	100%	99%	79.2



(a) (b)

Figure 6. Energy consumption in five different postures a) data rate = 1600 bps b) data rate = 6400 bps.



(a) (b)

Figure 7. Distribution of usage of different power levels during different postures in LPA a) data rate = 1600 bps, b) data rate = 6400 bps.

lated through the summation of energy consumed per packet transmission. Since the retransmission at the MAC sublayer is disabled, the protocols with fixed power levels consume a constant amount of energy no matter if the channel quality is good (e.g. sitting) or bad (e.g. standing). However, LPA adaptively decreases power level (and consequently energy usage) when the channel quality is good or partially good. As shown in Figure 6, the energy consumption of LPA is as low as FLP for sitting and driving which have the LoS between the sensor and the gateway and the distance between them is no more than a few dozens of centimeters. In other scenarios, LPA can reduce packet loss by increasing power level adaptively, as shown in both Figure 5 and Figure 6.

The usage of different power levels by LPA is shown in Figure 7 under the two different data rates. As expected, when the channel quality is good LPA chooses more often the lower powers such as level 1 and 2 in order to decrease energy consumption and interference. On the other hand, when the channel quality is bad, power level 3 and 4 are more often chosen to overcome body blockage. As shown in the figure, when the subject is running or walking, more than 90% of the packets are sent by level 3 and 4. However, lower power levels could be used in these scenarios. Because of the nature of walking and running, the channel quality switches between two states : good (e.g. position (d) and (e) in Figure 2) and bad (e.g. positions (a), (b) and (c) in the same figure). An ideal adaptive communication protocol should be able to send more packets with lower power levels opportunistically when the channel quality becomes good. This shows the limit of LPA which is not adaptive enough to fast movements, though it is much better than other adaptive protocols [8]–[11].

C. Experimental Results of Combined Multiple Scenarios

In this section, the five different scenarios are combined in a 5-minute daily activity to have a comprehensive comparison between LPA and the two protocols with fixed power levels. Table II summarizes the results of the experiments and shows energy consumption, reliability and usage distribution of different power levels for different protocols with different data rates. The results in Table II show that LPA has achieved the objective reasonably well. From the table, we can see the energy consumption of LPA is around half of the energy consumption of the FHP protocol, while the communication reliability of LPA is still high enough (only 4.3% fewer than FHP). In LPA, around 40% of the packets have been sent by level 1, which shows LPA can decrease transmission power level adaptively when the channel quality is good. On the other hand, about 22% of the packets have been sent by level 4, which means LPA can adaptively increase its transmission power when the channel is blocked.

As expected, communication with FLP is unreliable. From the table, we can see that almost 50% of the packets have been lost for FLP protocol. Note that although FLP is very energy efficient, packet loss rate can reach 100% in many postures like standing when the channel is completely blocked for a long time. This unreliability is not acceptable in many applications like ambulatory monitoring systems in which sensors have to send the vital measurements to the gateway with minimum

Table III
RELIABILITY AND ENERGY CONSUMPTION OF DIFFERENT PROTOCOLS WITH AND WITHOUT RETRANSMISSION FOR LOW DATA RATE COMMUNICATION

Protocol	Reliability in Different Postures					Total Reliability	Energy Consumption (mW)
	sitting	driving	standing	walking	running		
LPA without retransmission	97.67%	97.33%	71.67%	97.67%	97%	92.27%	0.364
LPA with retransmission	100%	100%	100%	100%	100%	100%	0.447
FLP without retransmission	95.90%	97.77%	0%	44.43%	38.5%	55.32%	0.075
FLP with retransmission	100%	100%	0%	100%	100%	80%	0.246
FHP without retransmission	100%	100%	99.67%	98.83%	98.5%	99.4%	0.99
FHP with retransmission	100%	100%	100%	100%	100%	100%	1

delay. On the other hand, the FHP protocol is quite reliable and only 1% of the packets have been lost. However, its energy consumption is more than 13 times greater than the FLP protocol. Moreover, according to Table I, its large transmission range potentially produces noise to other WBANs in the range.

D. Low data rate communication under retransmission

As explained, data rate in WBANs depends on the application but in most health care scenarios, an extremely low data rate is needed because vital signals like heart rate, blood pressure, and body temperature do not change very fast. In this section, we consider a low data rate scenario in which, sensor node sends one packet per two seconds. We also run the experiments for both enabled and disabled retransmission at MAC sublayer separately. The maximum number of retransmissions is set to seven and the time interval between retransmissions after an unsuccessful transmission is increased exponentially. The rest of the setup is similar to the previous experiments.

The reliability and energy consumption of different protocols in different postures are shown in Table III. As it can be seen, the reliability of LPA in standing is much less than the same posture in previous experiments when retransmission is disabled. This big difference is because of the way LPA estimates the channel. Since LPA is a feedback based protocol, when the data rate is high (40 packets per second), it learns sooner than the time the data rate is low. So, with the equal experiment time, LPA is better in terms of reliability when the data rate is higher and the channel is blocked. As the results show, the reliability of communication with LPA and FHP is reached to 100% when the retransmission is enabled. Although the biggest improvement is achieved by FLP (around 25%), the reliability of communication in standing remains unchanged. On the other hand, as the reliability of all protocols are improved, their energy consumptions are increased as well. As the results show, there is a sharp increase in energy consumption of FLP protocol when the retransmission is enabled (almost 328% increment) while energy consumption of LPA and FHP is increased only 22.8% and 1% respectively.

VI. CONCLUSION

In this paper, we developed LPA, a learning-based power aware communication protocol for WBANs which interacts with the gateway to discovering the channel status. LPA is light weight and easy-to-implement protocol which decreases energy consumption and interference range in different postures remarkably. Because of its learning-based nature, LPA does not need any information about the network topology. When the channel varies fast (e.g. in running), the performance of LPA is decreased significantly while it can be improved by multi-hop LPA. In multi-hop LPA, the sensor node is able to replace its one-hop communication with two or multi-hop communication whenever LoS is blocked.

REFERENCES

[1] A. Astrin *et al.*, “IEEE standard for local and metropolitan area networks part 15.6: Wireless body area networks: IEEE std 802.15.6,” *The document is available at IEEE Xplore*, 2012.

[2] J.-M. Choi, H.-J. Kang, and Y.-S. Choi, “A study on the wireless body area network applications and channel models,” in *Second IEEE International Conference on Future Generation Communication and Networking (FGCN)*, 2008, pp. 263–266.

[3] “IEEE p802.15.6/d0 draft standard for body area network,” 2010.

[4] J. I. Bangash, A. H. Abdullah, M. H. Anisi, and A. W. Khan, “A survey of routing protocols in wireless body sensor networks,” *Sensors*, vol. 14, no. 1, pp. 1322–1357, 2014.

[5] X. Cai, J. Li, J. Yuan, W. Zhu, and Q. Wu, “Energy-aware adaptive topology adjustment in wireless body area networks,” *Telecommunication Systems*, vol. 58, no. 2, pp. 139–152, 2015.

[6] J. Elias and A. Mehaoua, “Energy-aware topology design for wireless body area networks,” in *IEEE International Conference on Communications (ICC)*, 2012, pp. 3409–3410.

[7] E. Reusens, W. Joseph, B. Latré, B. Braem, G. Vermeeren, E. Tanghe, L. Martens, I. Moerman, and C. Blondia, “Characterization of on-body communication channel and energy efficient topology design for wireless body area networks,” *IEEE Transactions on Information Technology in Biomedicine*, vol. 13, no. 6, pp. 933–945, 2009.

[8] P. Kindt, H. Jing, N. Peters, and S. Chakraborty, “Experio - exploiting periodicity for opportunistic energy-efficient data transmission,” in *IEEE Conference on Computer Communications (INFOCOM)*, 2015, pp. 82–90.

[9] M. Quwaider and S. Biswas, “Probabilistic routing in on-body sensor networks with postural disconnections,” in *Proceedings of the 7th ACM international symposium on Mobility management and wireless access*, 2009, pp. 149–158.

[10] ——, “DTN routing in body sensor networks with dynamic postural partitioning,” *Ad Hoc Networks*, vol. 8, no. 8, pp. 824–841, 2010.

[11] S. Yang, J.-L. Lu, F. Yang, L. Kong, W. Shu, and M.-Y. Wu, “Behavior-aware probabilistic routing for wireless body area sensor networks,” in *IEEE Global Communications Conference (GLOBECOM)*, 2013, pp. 444–449.

[12] K. S. Narendra and M. Thathachar, “Learning automata-a survey,” *IEEE Transactions on Systems, Man and Cybernetics*, no. 4, pp. 323–334, 1974.