Energy Saving Efficiency Comparison of Transmit Power Control and Link Adaptation in BANs

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***Abstract*—The wireless channels in Body Area Networks (BANs) have significant temporal variations due to body movements. Therefore there is a potential to save energy by exploiting adaptive schemes, such as transmit power control (PC) and link adaptation (LA). This paper investigates the energy saving efficiency of PC and LA in BANs. The theoretical bounds of energy saving efficiency of PC and LA, and the condition that LA outperforms PC are derived. Generally speaking, LA is more efficient in saving energy than PC in BANs. The energy saving efficiency and packet erasure rate (PER) of PC and LA are evaluated through simulations with a large measured dataset from a BAN testbed. The simulation results show that LA can save 80-85% more energy than PC during 80% time. The increased PER due to the adaptive schemes is below 1% during 80-95% time at the different links.**

I. Introduction

Wireless Body Area Network (BAN) is an emerging technology to continuously collect physiological data for diagnosis or deliver various personalized therapeutic treatment related applications and services. The sensor nodes in BANs are required to be small and lightweight to be able to deliver the level of comfort and unobtrusiveness [1]. This requirement sets the limitation on the battery size and makes energy efficiency even more crucial. The common goal of various energy efficient solutions is to make sensor nodes adapt energy consumption in response to the changes in the environment, by which to minimize energy usage. All layers in the system from transceiver architecture to network protocol and algorithm can exploit energy efficient design; nevertheless, it is critical that energy efficient protocol and algorithm is based on accurate modeling of the underlying hardware [2]. The wireless channels in BANs have significant temporal variations due to body movements [1], [3], [4]. The fluctuation of the path loss can reach ± 30 dB around the median [1]. Therefore, there is a potential in energy saving by using adaptive schemes. Transmit power control (PC) and link adaptation (LA) are the two possible adaptive schemes widely used for the dynamic wireless channels. Transmit power control have been used to save energy in BANs [5]–[7]. Rate adaptation used to save energy in WSNs has been addressed in [8].

This paper evaluates PC and LA schemes by considering the overall energy consumption at the transmitter and receiver, including both RF transmission and transceiver circuit energy consumption. It is aiming to answer the following questions. What impacts the theoretical bound of energy saving in PC and LA, respectively? How much energy saving can be achieved by the adaptive schemes in the real BAN links?

The theoretical analysis shows that in BANs PC is not efficient in saving energy as in short-range communication systems the RF transmit power is much smaller than the power consumption of the transceiver circuit. The energy saving efficiency of PC depends on the average current at the transmitter and receiver. For a given transceiver the maximum energy saving efficiency of PC is bounded by the current at the receiver and the minimum current at the transmitter. The energy saving efficiency of LA is monotonically increases when the average data rate increases. LA is more efficient in saving energy than PC, if it meets the condition that the average data rate exceeds a threshold which is determined by the average current at the transmitter and receiver in PC. According to the data sheets of the transceivers off-the-shelf, this condition holds. The performance of PC and LA is evaluated by a simulation with a large dataset collected from an open-source BAN testbed [9]. The simulation results show that LA is more energy efficient than PC. LA can save about 80-85% more energy during 80% time and in the worst case 50% more energy can be saved. Furthermore, the implemented LA and PC schemes have similar packet erasure rate (PER). Comparing with the static scheme the increased PER of PC is below 1% during 80-95% time for different links.

This paper is organized as follows. The related work is presented in Section II. Section III and IV describe transmit power control and link adaptation schemes, respectively. Section V theoretically compares LA and PC in energy saving efficiency and derives the theoretical bounds and condition. The performance of LA and PC are evaluated through simulation in Section VI. The conclusion is reached in Section VII.

II. Related Work

Many researchers have worked on dynamic transmit power control as a means to save energy in wearable BANs, such as [5]–[7]. S. Xiao et al. [5] proposed a dynamic PC scheme which can adapt transmit power by comparing the running RSSI average to the pre-defined lower and upper threshold. The theoretical benefit of adaptive transmit PC can save nearly 35% energy without compromising reliability across different scenarios in [5]. In practice, comparing to the case of using maximum transmit power it can save 14-30% energy in exchange for 1-10% packet losses. M. Quwaider et al. [6] developed several customized approaches for transmit PC via tracking of postural node mobility. It evaluated the performance based on Mica2Mote using radio chip CC1000. With one of the proposed PC schemes, DPPI, it can save 43-50% energy for different testing persons, comparing to using the maximum transmit power. D. Smith et al. [7] proposed a novel channel prediction which can effectively predict the channel state in BANs up to 2s ahead. The dynamic transmit PC using the novel predictor can both reduce transmit power and improve reliability. It declared that 8-22% energy was saved comparing with a constant transmit power of 10 dBm.

A. Wang et al. has explained in [10] that data rate does not scale with power consumption due to the fixed power consumption cost of the transmitter electronics. According to [11], the power consumption of transceiver circuit electronics is fixed when the data rates are below 10 Mbps[1]. This conclusion indicates that increasing data rate can save energy on transmission and receiving due to the shortened transmission and receiving time. [11], [12] also addressed that the power consumption is dominated by the circuit electronics (e.g., frequency synthesizer, mixer, etc.) for short-range RF transceivers operating in the Giga-Hertz carrier frequency range. Furthermore, [12] has shown that M-ary modulation may enable energy savings over binary modulation for some short-range applications by reducing the transmission and receiving time.

S. Lanzisera et al. [8] have looked into using data rate adaptation to save energy in wireless sensor networks. It inferred the link quality based on RSSI or LQI measurement. Then based on the link quality it realized rate adaptation through adapting the spreading factor of direct sequence spread spectrum used in 802.15.4. It stated that about 40% average energy saving was achieved in their testbed. F. Martelli et al. [13] proposed to use link adaption by selecting different modulation schemes aiming to reduce packet losses in BANs.

III. Transmit Power Control

The basic idea of transmit PC is to optimally select an RF transmit power to achieve the required performance (e.g., network capacity, reliability, energy consumption etc.) at a constant data rate. Transmit PC is often used as a means to avoid near-far effect or a means of interference mitigation in interference limited wireless communication system, such as WCDMA cellular networks. PC has also been used in mobile handset in cellular networks to save energy. Cellular network is a typical long-range communication system (i.e., transmission distance $\geq$ 100 m) and power consumption of power amplifier (PA) dominates the transceiver power consumption at handset. The power consumption of PA, P_{PA}, can be simply represented by RF transmit power, P_{out}, and efficiency of PA, η_{PA}, as $P_{PA} = P_{out}/\eta_{PA}$.

The *transceiver energy efficiency*, η, is defined by [11].

$$\eta = \frac{P_{out}}{P_{PA} + P_{cic}^{tx} + P_{cic}^{rx}}$$

[1]The power consumption of the circuit blocks will increase with data rate when the data rates beyond a few 10's Mega-bits per second [11].

Where, P_{cic}^{tx}, P_{cic}^{rx} are the power consumption of circuit block in transmitter and receiver, respectively.

When PA dominates the transceiver power consumption (e.g., long-range communication systems), $P_{cic}^{tx} + P_{cic}^{rx}$ is very small comparing to P_{PA}. Hence, η can be approximated as [11]

$$\eta \approx \frac{P_{out}}{P_{PA}} = \eta_{PA}$$

Efficiency of PA, η_{PA}, can vary quite a bit depending on PA type, RF transmit power, technology and design. Normally η_{PA} decreases quickly with decreasing output power [8], nevertheless, for simplicity a fixed efficiency of PA, η_{PA}, is assumed here. Then it is clear that the energy consumption will approximately scale linearly with the RF transmit power. Therefore, in a system that PA power consumption is dominant, PC can be quite efficient in saving energy. For example, ideally reducing P_{out} by 3dB can approximately reduce half of the energy consumption at the transmitter. If considering the total energy consumption at both transmitter and receiver, the energy saving will be less than 50%, because PC cannot save energy at the receiver.

However, in low power short-range communication system (i.e., transmission distance $<$ 10 m), such as BANs and WSNs, the power consumption of transceiver electronics dominates. P_{PA} is about an order of magnitude less than the power consumption of transceiver electronics. Thus *transceiver energy efficiency* η can be approximated as [11]

$$\eta \approx \frac{P_{out}}{P_{cic}^{tx} + P_{cic}^{rx}}$$

We can see that *transceiver energy efficiency* η goes down when reducing the RF transmit power. In such a system the energy consumption does not scale linearly with the RF transmit power; therefore, PC is not efficient in energy saving. Taking a widely used radio chip in WSNs, CC2420 [14], as an example, when reducing P_{out} from 0 dBm to -3 dBm, it can reduce the transmitter energy consumption by only 12.79% not 50%. If taking the energy cost at the receiver into account, the energy saving is only about 6%.

IV. Link Adaptation

The basic idea of link adaptation (LA) scheme is to adapt data rate by selecting a suitable modulation and coding scheme at a constant transmit power. The goal of LA is to transmit a certain amount of data using minimum resource at an acceptable reliability. The resource could be energy, time, frequency spectrum, and many others. LA is suitable to be used in an environment with dynamic path loss and channel quality. The reason is as follows. In a static scheme, the data rate and transmit power are fixed. In order to work properly in the worst case a static scheme usually has to transmit at the lowest data rate. The problem of the static scheme is obvious that it misses the opportunities of transmitting at a higher data rate when the channel is good. Comparing with the static scheme, LA has a potential to save energy, reduce channel occupation time, improve spectrum efficiency and others. We focus on energy saving in this paper as energy is one of the crucial challenges in BANs.

When the transmit and receiving power is fixed, the energy consumption scales linearly with time. The saved energy by LA results from the reduced transmission and receiving time at the transmitter and receiver. Hence, the saved energy scales linearly with the reduced transmission and receiving time. For example, by changing spreading factor from 4 to 2, it can save approximately 50% energy.

V. Link Adaptation vs. Power Control

To compare the energy saving efficiency of LA and PC, a generic energy model is used. In this model the transition time between sleep and active is not considered. If the transition time is longer than the active duration, LA cannot give too much payoff. However, if a transceiver has a long transition time, a short active duration should be avoided in scheduling design.

TABLE I
Denotations used in Section V

Notation	Meaning	Unit
P_{tx}	overall power consumption at transmitter	mW
P_{rx}	overall power consumption at receiver	mW
t	transmission (receiving) time	s
V	voltage	volt
I_0	current at maximum transmit power = 0 dBm	mA
I_r	current for receiving	mA
R_0	minimum data rate	kbps
I_i	current at transmit power setting i	mA
$\overline{I_i}$	mean current at transmitter with PC	mA
R_j	data rate setting j	kbps
$\overline{R_j}$	mean data rate with LA	kbps
E_{pc}	total energy consumption with PC	mJ
E_{la}	total energy consumption with LA	mJ
E_0	total energy consumption with static scheme	mJ
L	packet size	bit
N	total number of packets	
ξ_{pc}	energy saving efficiency with PC	
ξ_{la}	energy saving efficiency with LA	
ξ	energy saving efficiency of LA over PC	

The basic static scheme is assumed to use a constant transmit power at a fixed data rate (i.e., the maximum transmit power and the minimum data rate). Assuming no packet loss, the total energy consumption of the static scheme used to transmit N packets from the sender to the receiver, E_0, basically includes the energy spent on transmission and receiving, respectively. It can be calculated as

$$\begin{aligned} E_0 &= (P_{tx} + P_{rx})t \\ &= V(I_0 + I_r)\frac{NL}{R_0} \end{aligned}$$

Where, $P_{tx} = P_{PA} + P_{cic}^{tx}$ and $P_{rx} = P_{cic}^{rx}$.
Assume $I_r = \gamma I_0$,

$$E_0 = (1+\gamma)\frac{VI_0NL}{R_0}$$

With PC, the current at the transmitter varies based on the different transmit power, which results in the variations of the power consumption at the transmitter. Nevertheless, PC has no impact on the power consumption at the receiver. Thus, the energy used to transmit N packets from the sender to the receiver with PC scheme, E_{pc}, can be expressed as

$$E_{pc} = V\sum_{n=1}^{N}(I_i + I_r)\frac{L}{R_0}$$

Assume the mean current over the transmission of the N packets $\overline{I_i} = \alpha I_0$, where $\alpha \leq 1$. Then there is

$$\begin{aligned} E_{pc} &= V(\alpha I_0 + \gamma I_0)\frac{NL}{R_0} \\ &= (\alpha+\gamma)\frac{VI_0NL}{R_0} \end{aligned}$$

With LA, the transmission and receiving time varies based on the different data rate. Traditionally a change in modulation, for example, from a basic BPSK to M-PSK, would cause an increase in power consumption of transceiver electronics due to the fact that a quadrature modulator would have to be employed in order to support the inherent increase in phase resolution. [12] also tried to model the increased power in M-ary modulation on the frequency synthesizer and other circuit. However, in the case of an IEEE 802.15.6 compliant transmitter this is not the case, because the defined binary modulation scheme consists of a $\pi/2$ rotated version of a DBPSK [15]. The rotation is only possible by employing the quadrature modulator circuitry. Therefore, power consumption will not significantly increase in the transceiver electronics by switching from $\pi/2$ DBPSK to $\pi/2$ DQPSK. The power consumption at the transmitter and receiver is assumed to be constant here. Thus, the total energy used to transmit N packets from the sender to the receiver with LA can be expressed as

$$E_{la} = V(I_0 + I_r)\sum_{n=1}^{N}\frac{L}{R_j}$$

Assume the mean data rate over the transmission of the N packets $\overline{R_j} = \beta R_0$, where $\beta \geq 1$. Then there is

$$\begin{aligned} E_{la} &= V(I_0 + \gamma I_0)\frac{NL}{\beta R_0} \\ &= \frac{1+\gamma}{\beta}\cdot\frac{VI_0NL}{R_0} \end{aligned}$$

Comparing with the static scheme, the energy saving efficiency with transmit PC can be calculated as follows.

$$\begin{aligned} \xi_{pc} &= (E_0 - E_{pc})/E_0 \\ &= \frac{1-\alpha}{1+\gamma} \end{aligned} \quad (1)$$

From Equation 1, it shows that the energy saving efficiency of PC depends on the average current at the transmitter and the current at the receiver. The maximum energy saving efficiency of PC is bounded by the current at the receiver and the minimum current at the transmitter, i.e., $\xi_{pc} \leq \frac{1-\alpha_{min}}{1+\gamma}$. For example, as we know in BANs, the power consumption of transceiver electronics dominates. The current at a receiver could be very high and even higher than the maximum current at a transmitter. Hence, the energy saving efficiency of PC could be quite low. This is consistent with the analysis in Section III.

Comparing with the static scheme, the energy saving efficiency of LA, ξ_{la}, can be calculated in the following.

$$\xi_{la} = (E_0 - E_{la})/E_0 = 1 - \frac{1}{\beta} \quad (2)$$

Equation 2 shows that the energy saving efficiency of LA only depends on the average data rate, i.e., ξ_{la} monotonically increases when the average data rate increases.

To tell whether LA is more efficient than PC in saving energy, we can compare E_{pc} and E_{la} as follows.

$$\begin{aligned} \xi &= (E_{pc} - E_{la})/E_{pc} \\ &= 1 - \frac{1+\gamma}{\beta(\alpha+\gamma)} \end{aligned} \quad (3)$$

Equation 3 shows that as long as $\beta > \frac{1+\gamma}{\alpha+\gamma}$ link adaptation will outperform power control in saving energy.

VI. Performance Analysis

A. Numerical Analysis

In this subsection, we will look at the limit of the energy saving efficiency with PC for the radio chips off-the-shelf. Table II lists some relevant data of radio chips: CC2420 [14], CC1000 [16], CC2520 [17] which are often used in WSNs. Δ_{out} is the difference of the minimum transmit power comparing to 0 dBm. From Table II we can see that the *transceiver energy efficiency* is very low in these transceivers for short-range communications. Based on the data, we obtain the maximum energy saving efficiency of PC, ξ_{pc}^{max}, for different transceivers, which is in the range of $(0.1970, 0.3028)$.

TABLE II
I_0, I_{min}, I_r of different ratio chips

Radio Chip	CC2420	CC1000	CC1000	CC2520
Frequency (MHz)	2400	433	868	2400
I_0 (mA)	17.4	10.4	16.5	25.8
η_{max}	0.92%	1.87%	1.28%	0.75%
I_{min} (mA)	8.5	6.9	8.6	16.2
Δ_{out} (dB)	25	20	20	18
I_r (mA)	18.8	7.4	9.6	18.5
α_{min}	0.489	0.663	0.521	0.628
γ	1.08	0.711	0.582	0.717
ξ_{pc}^{max}	0.2457	0.1970	0.3028	0.2167

Generally, the receiver sensitivity is assumed to approximately deteriorate 3 dB when the data rate is doubled. For example, by decreasing spreading factor by half, the data rate is doubled but 3 dB processing gain is lost. Or by switching from BPSK to QPSK, the energy per symbol to noise density ratio E_s/N_0 increases 3 dB. The maximum data rate is assumed to be eight times of the minimum data rate in LA, although LA is not widely supported by the transceivers off-the-shelf. Based on these assumptions, when the path loss is reduced by 3 dB, with transmit PC ideally it can reduce the transmit power by 3 dB or alternatively it can double the data rate with LA.

We denote $\beta^{th} = \frac{1+\gamma}{\alpha+\gamma}$ the threshold of β that LA is more efficient than PC in saving energy. Table III lists β^{th} for CC2420 and CC2520 as example. It is clear that the condition $\beta \geq \beta^{th}$ always holds.

TABLE III
Threshold of link adaptation outperforming power control in CC2420 and CC2520.

P_{out} (mW)	α_{CC2420}	β^{th}_{CC2420}	α_{CC2520}	β^{th}_{CC2520}	β
1	1	1	1	1	1
0.5	0.8736	1.0647	0.9259	1.0451	2
0.25	0.7529	1.1348	0.8028	1.1298	4
0.125	0.6624	1.1938	0.7131	1.2006	8

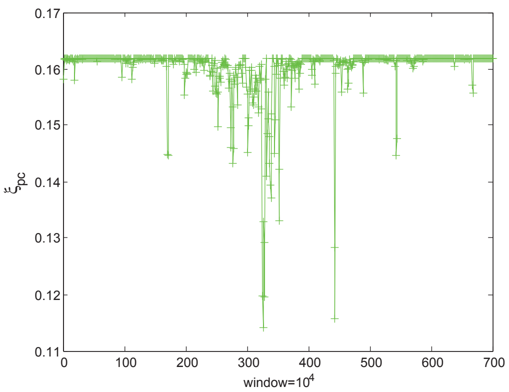
B. Simulation Results

To evaluate the energy saving efficiency of LA and PC in BANs, we apply the two adaptive schemes to a large dataset in the simulation. The dataset was continuously sampled at 200 Hz over 12 hours with transmit power 0 dBm in a wearable BAN testbed at NICTA [9], [18], [19]. A simple LA algorithm and a PC algorithm were implemented in the simulation. Perfect feedback is assumed in the simulation, which just provides an equal condition for comparision of LA and PC. The basic idea of LA is that if the RSSI at the receiver is higher than the current receiver sensitivity, then it selects a suitable data rate setting for the next transmission and updates the receiver sensitivity based on the selected data rate. If the RSSI is below the current receiver sensitivity, then the packet is regarded as lost. A lower data rate should be selected for the next packet transmission. Regarding how to adapt data rate, there could be many options. A step-wise increase and fast decrease algorithm is implemented in the simulation. Note that in the simulation the packet erasures in LA are the original packet erasures in the real measurement plus those below the receiver sensitivity. The data rate options for LA are based on what is defined in IEEE 802.15.6 standard [15] (see Table IV).

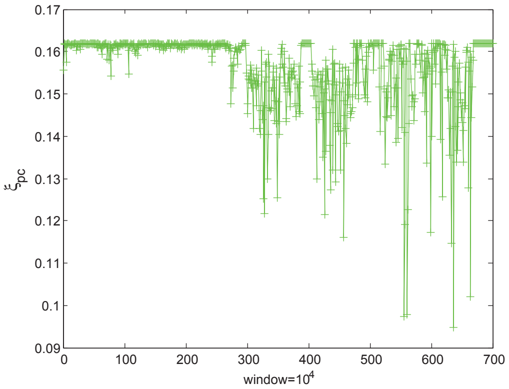
TABLE IV
Data rate defined in IEEE 802.15.6 at 2400-2483.5 MHz [15]

R_j	Modulation	Spreading Factor	Data Rate (kbps)	Receiver Sensitivity (dBm)
R_1	$\pi/2$ DBPSK	4	121.4	-92
R_2	$\pi/2$ DBPSK	2	242.9	-90
R_3	$\pi/2$ DBPSK	1	485.7	-87
R_4	$\pi/2$ DQPSK	1	971.4	-83

The basic idea of the PC algorithm is that if the current transmit power minus the path loss is higher than the basic receiver sensitivity -92 dBm, then it calculates a new transmit power and sends the next packet at the new transmit power. If the current transmit power minus the path loss is below -92 dBm, the packet is regarded as lost. There could be different strategies to adapt the transmit power. Similarly to LA, a step-wise decrease and fast increase strategy is used in the simulation. To make a comparison with LA in energy saving, the PC algorithm can select one of the transmit power in the set of $[0, -2, -5, -9]$ dBm which is derived based on the receiver sensitivity given in Table IV.

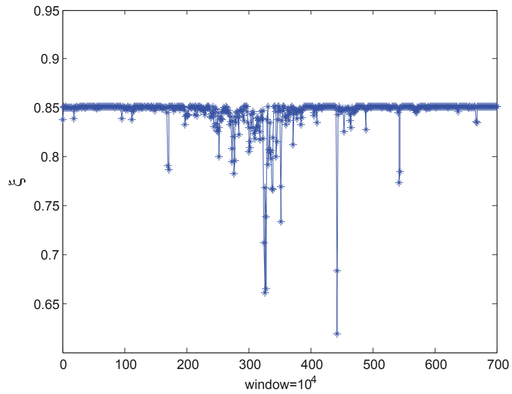


(a) The link of the right hip → the right ankle.

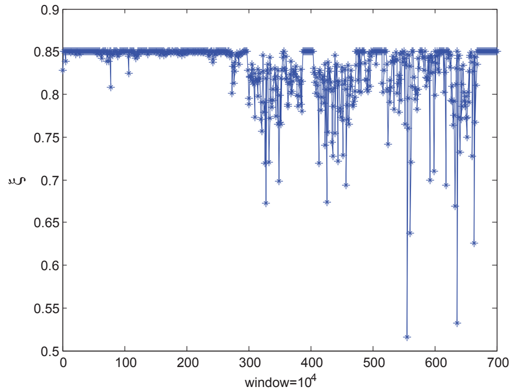


(b) The link of the right hip → the right wrist.

Fig. 1. The energy saving efficiency of power control.



(a) The link of the right hip → the right ankle.



(b) The link of the right hip → the right wrist.

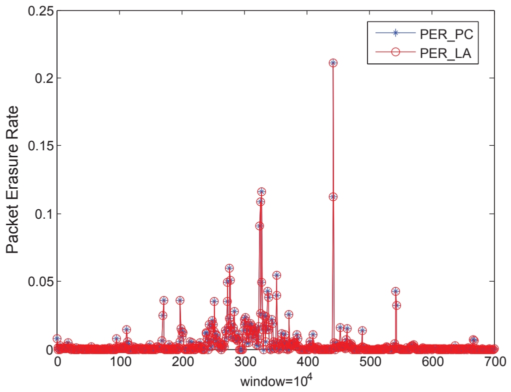
Fig. 2. The energy saving efficiency of link adaptation over power control.

In the simulation, the voltage and current data is taken from the data sheet of radio chip CC2420 [14]. Each value is averaged over 10^4 samples (i.e., window = 10^4). Figure 1(a) and 1(b) show the energy saving efficiency of PC for the links from the right hip to the right ankle and from right hip to the right wrist, respectively. We can see that comparing with the static scheme, PC can at most save approximately 16% energy. The energy saving efficiency can drop below 10% in the worst case. Figure 2(a) and Figure 2(b) show how many percent that LA is more efficient than PC. We can see that similarly to Figure 1 the energy saving efficiency in Figure 2 varies over time owing to the time-variant channel characteristics in BAN. In the links to the right ankle and to the right wrist, the LA can save 80-85% more energy than PC during 80% time. And in the worst case, LA can still save about 50% energy more than PC, in other words, in the worst case LA only uses half of the energy used by PC.

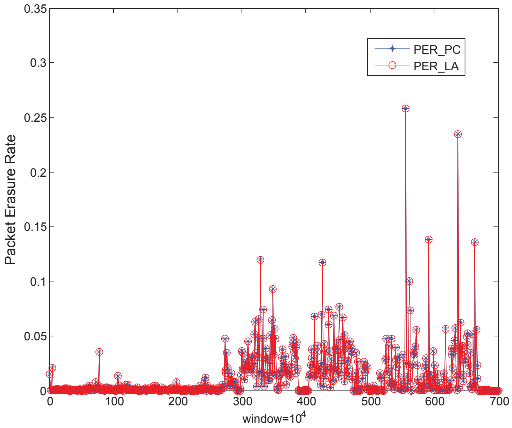
Figure 3(a) and Figure 3(b) show the packet erasure rate (PER) with LA and PC at the two links. We can see that with the simple LA and PC algorithms, the PER of these two adaptive schemes are almost same. Generally the PER is below 5%. There are a few burst losses in which the PER can reach 20-25% which includes the original packet losses with static scheme. Hence, it is necessary to see the increased PER introduced by LA and PC comparing with the static scheme. Figure 4 shows the empirical cumulative distribution function of the increased PER owing to PC. This figure can also represent the increased PER by LA, as the PER of LA is nearly the same as that of PC. It shows that this simple PC algorithm introduces below 1% additional packet erasures during 80-95% time at different links. In the worst case this algorithm introduces at most 5% additional packet erasures. Of course, there are other work such as [6], [7], [13] focusing on designing advanced algorithms to optimize the reliability and energy saving. It can be expected that the increased PER will be smaller if applying more advanced LA or PC algorithms.

VII. Conclusion

This paper compares the energy saving efficiency of link adaptation and power control in BANs based on a generic energy consumption model. It sheds a light on how the average current at the transmitter and receiver, and the average data rate determine the energy saving efficiency of LA and PC. The condition that LA outperforms PC is also derived. Furthermore, to evaluate the energy saving efficiency, the simulation has applied the simple PC and LA algorithms to a large dataset measured in a BAN testbed. The simulation results show that LA is more efficient to save energy in BANs



(a) The link of the right hip → the right ankle.



(b) The link of the right hip → the right wrist.

Fig. 3. Packet erasure rate of link adaptation and power control.

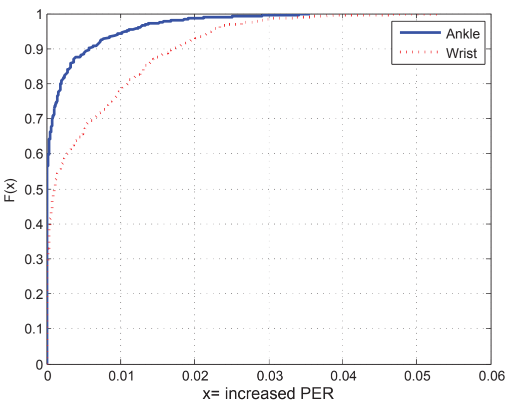


Fig. 4. The empirical cumulative distribution function of the increased PER owing to power control.

and it can save about 80-85% more energy than PC during 80% time. In terms of PER, LA and PC have similar performances. Comparing with the static scheme, the additional packet erasures introduced by the adaptive schemes is below 1% during 80-95% time.

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