Buffer Delay Improvement in Gait-Cycle-Driven Transmission Power Control Scheme for WBAN

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***Abstract*—Due to the dynamic nature of the wireless body area network (WBAN) channels, there is a need for dynamic transmission power control (TPC) to increase their energy efficiency. The existing gait-cycle-driven TPC (G-TPC) successfully achieves this objective, however, it introduces maximum buffer delay equal to the period of the gait cycle. In this study, we investigate the relationship between the potential power saved and the maximum buffer delay in the G-TPC approach. A new approach is proposed based on the transmission window (instead of currently used transmission point) to reduce the maximum buffer delay by studying the received signal strength indicator (RSSI) gait patterns collected from 20 subjects. The results indicated that with a slight modification of the protocol, the same power saving can be achieved for 1.2% of the time with less than half of the maximum buffer delay. The study also indicated that, with tolerant power-saving requirements, at least half of the gait channels can reduce the maximum buffer delay by more than 38%.**

***Index Terms*—Wireless body area network, transmission power control, gait cycle, buffer delay, energy efficiency.**

I. Introduction

Recent advances in wireless communication and miniaturization of sensors has lead to the growth of the field known as wireless body area networks (WBANs). These WBANs find various applications such as health monitoring, sports activities, and specialized occupations such as paramedics, and firefighters [1]. The networks incorporate several sensor nodes placed in, on, or around the human body to monitor the human physiological data. The collected data by the sensor nodes are then relayed to the on-body central coordinator for processing, and forwarding if needed to remote locations [2].

Most sensor nodes in WBANs are limited in size and hence have limited energy resources [3]. As the transceiver is known to be the most energy-consuming part in a sensor node, preserving energy by minimizing the transmission power is therefore crucial in the lifetime of the WBAN nodes. However, this could lead to unreliable communication as radio transmission in the vicinity of the human body is highly lossy and inefficient [4]. Also, due to the dynamic nature of the concerned channels, static transmission power can result in either poor energy efficiency or low reliability as the link quality endures large drastic fluctuations [5]. These constraints among others make the study of transmission power control schemes as major design concern in WBANs.

Adaptive radio transmits power control based on received signal strength indicator (RSSI) were proposed in [6]–[8] as a means of saving energy in WBAN. In [7] on-body communication in a semi-dynamic environment was considered while the protocol in [6] was tested in off-body communication. The experiment in [6] showed that the protocol could save 14-30% energy in exchange for 1-10% packet losses. The work in [8] took into consideration the effect of interference on WBANs and proposes a transmission power control not only based on RSSI but also link quality indicator (LQI). This resulted in packet loss reduction of 21.6% by changing the transmission channel whenever interference is identified. Although these protocols work well in a defined environment, these studies did not take into consideration the energy cost of sending constant feedback information, as the central node was assumed to have abundant energy reserves. In addition, the feedback information fails to reflect the channel conditions when the link quality varies drastically which could be experienced in activities such as walking and running [5].

Another group of researchers tried to take advantage of the body movement to improve WBAN energy efficiency [5], [9], [10]. These algorithms involved scheduling the transmission so that it only occurs during the best possible channel conditions, and remained idle the rest of the time. This not only reduces transmission power but also guarantees reliability [5]. In [10], this protocol was implemented on the media access control (MAC) layer and resulted in the packet loss rate of nearly zero. The authors in [9] made use of an accelerometer, common in WBAN devices to obtain the user's gait cycle information and hence the time points of the ideal channel condition for transmission. The results reveal that energy consumption can be reduced by 25% on the sensor node and the packet loss rate can be reduced by 65% compared to conventional adaptive transmission power control schemes.

The gait-cycle-driven TPC (G-TPC) approach taken by researchers in [5], [9], [10] has its advantages, however since the transmission only occurs once for every walking cycle, it introduces buffer delay with its maximum value being equal to the period of the walking cycle [9]. In this work, the relationship between the maximum buffer delay and potential power saved in the G-TPC was investigated by studying the gait RSSI patterns collected from 20 subjects. From the relationship

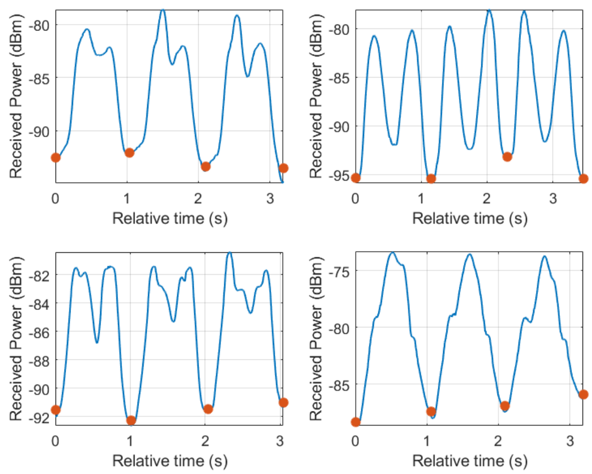

Fig. 1. Received power of 4 different subjects during 3 gait cycles.

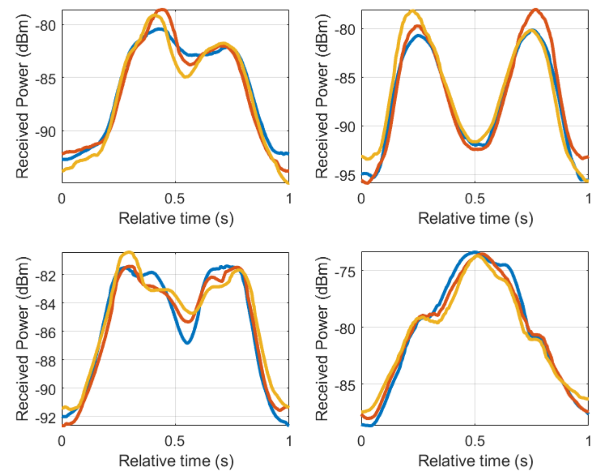

Fig. 2. Gait cycles plotted on top of each other. The received power is similar for the same user, but different between users.

a method of reducing the buffer delay without a significant reduction in the saved power is proposed.

The remainder of the paper is organized as follows. Section II describes the gait data collection process and analysis, Section III investigates the relationship between buffer delay and power saved, and Section IV concludes the paper.

II. Experimental Data and Analysis

A. Measurement Data

The gait RSSI patterns were collected from 20 healthy subjects, with different age, height, and weight. A receiver was attached on the wrist of the right arm representing a WBAN node such as a smartwatch and a transmitter was placed on the right side of the waist representing a WBAN coordinator such as a smartphone. To capture the natural gait changes over time and the influence of the different environment, the subjects walked continuously for 4 minutes outdoors and 4 minutes indoors. The transmitter was set to transmit a packet every 5 ms with a constant transmission power of 1 dBm at 2.425 GHz carrier frequency. The receiver stored the RSSI of each packet and were later transferred to a computer for analysis. Further details of the experiment are found in [11].

B. Data Analysis

It is well known that there is a periodic fluctuation of the RSSI during walking in a wrist-to-waist channel [5], [12], however, our measurement results also show that these fluctuations vary from one person to the other due to difference in size and gait [11]. The difference is not only noticed in the peak-to-peak value and the period of fluctuation, but also on the shape of the measured output. Not all subjects produced a sinusoidal RSSI output, and hence not all subject's channels are optimal only on one location.

Fig. 1 shows an example of the received power of 4 different subjects for 3 gait cycles, and Fig. 2 shows the gait cycles from Fig. 1 plotted on top of each other. The received power during walking is consistent for a given subject, however, it varies from one subject to the other. The shape varies from single peak, double peak, to a flat top with minor fluctuations. This means that the best link quality in each gait period is not limited to a point, but can be extended to one or multiple windows, depending on the gait and amount of energy to be saved. This has the potential of reducing the buffer delay of G-TPC.

III. The Transmission Window Approach

As discussed previously, the G-TPC proposed in [5], [9], [10] introduces maximum buffer delays which are equal to the gait cycle period. This is because transmission occurs only once in every gait cycle. To reduce the delays, a transmission window could be used instead of a transmission point. The transmission window can be defined as that time in which the RSSI is above a certain threshold and hence the channel can be considered good enough for transmission while saving enough power. Specifically, we propose the transmission not only to occur at an instant of the best channel condition but extend it to a larger window as long as it meets certain channel conditions such as minimum RSSI.

A. Maximum Buffer Delay and Saved Transmission Power

It is evident that the size of the transmission window will depend on the power saving condition to be met, defined by the threshold RSSI value. In a more strict power-saving condition, the RSSI value will be set to high values, making the transmission window small and the maximum buffer delay large. The opposite is also true, that is with a smaller RSSI threshold the transmission window becomes larger, and both the maximum buffer delay and the potential power saved become smaller. This relationship is not linear and varies from one RSSI gait pattern to the other.

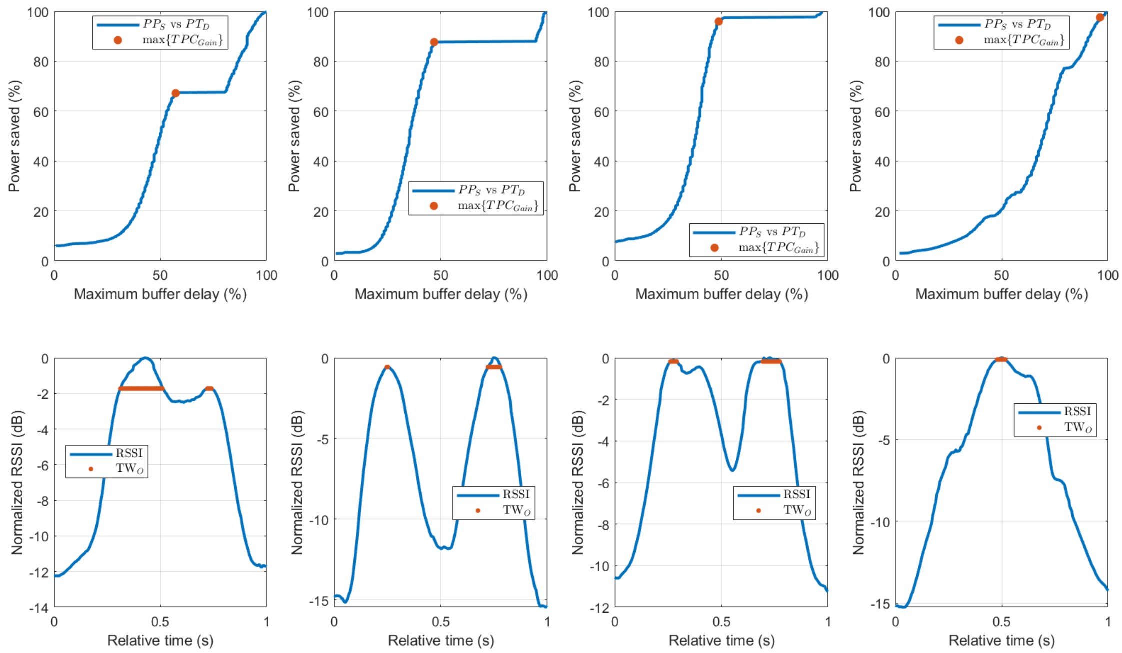

Fig. 3. Top row, the relationship between percentage power saved and percentage maximum buffer delay for different gait. The point of max$\{TPC_{Gain}\}$ is indicated by a red dot. Bottom row, the RSSI values for the corresponding gait. The optimal transmission window TW$_O$ is indicated by red dots.

Let us express the maximum buffer delay T_D encountered using a given transmission window in percentage as

$$PT_D = \frac{T_D}{T_G} \times 100 \tag{1}$$

where 100% delay represents a delay equals to gait period T_G. Let us also express the power saved P_S achieved using a given transmission window in percentage as

$$PP_S = \frac{P_S}{P_G} \times 100 \tag{2}$$

where 100% equals to power saved when transmission occurs only once per gait circle P_G. We can then introduce a term transmission power control gain TPC_{Gain} as

$$TPC_{Gain} = PP_S - PT_D \tag{3}$$

Then the optimal transmission window TW$_O$ is the one which results with high power savings, and low buffer delays possible. This is that window which gives the max$\{TPC_{Gain}\}$ for a given RSSI gait pattern.

The top row of Fig. 3 shows the relationship between the percentage power saved and the percentage maximum buffer delay for different RSSI gait patterns. The point of max$\{TPC_{Gain}\}$ is indicated by a red dot. The corresponding RSSI gait patterns and their optimal transmission windows TW$_O$ are plotted on the bottom row. Only the gait on the far right column has one instant of transmission per gait cycle which results in maximum buffer delay equal to the gait period. The remaining gait has TW$_O$ with two transmission instances hence reducing the maximum buffer delay to approximately half without much reduction in saved power.

B. Results and Discussion

Since the goal of G-TPC is to save power, then it becomes important to make sure that the optimal transmission window TW$_O$ also satisfies the minimum power-saving requirements PP_{min}. The optimal transmission window TW$_O$ is the window that not only gives you max$\{TPC_{Gain}\}$ but also satisfies the condition $PP_S > PP_{min}$. Fig. 4 shows the probability distribution of the power saved PP_S and the maximum buffer delay PT_D for the optimal transmission window TW$_O$ where the minimum power saving requirement is set to 50 percent ($PP_{min} = 50\%$). It can be observed that TW$_O$ with one instant of transmission is by far the most common with more than 35% of the windows falling in this category ($PP_S = 100$ and $PT_D = 100$). However, it is also interesting to see that 100% power saving can also be achieved with a maximum buffer delay as low as 30%.

Fig. 5 shows the cumulative probability of maximum buffer delay PT_D together with its corresponding quartiles for the optimal transmission windows TW$_O$ of different power saving requirement PP_{min}. For the more strict power requirements ($PP_{min} = 75\%$), only a quarter of the gait achieve a third of the maximum buffer delay reduction. However, for the more relaxed requirements ($PP_{min} = 50\%$ and $PP_{min} = 25\%$) half of the gait will have TW$_O$ with maximum buffer delay of less than 62% and 49% respectively, and a quarter will have TW$_O$ with

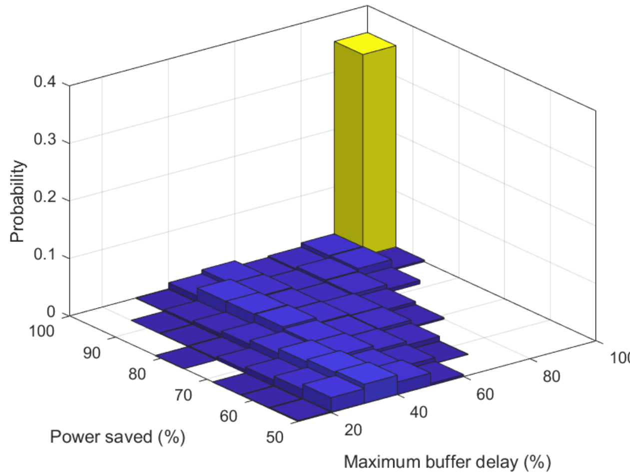

Fig. 4. The probability distribution of power saved PP_S and maximum buffer delay PT_D for the optimal transmission window TW_O where the minimum power saving requirement PP_{min} is set to 50%.

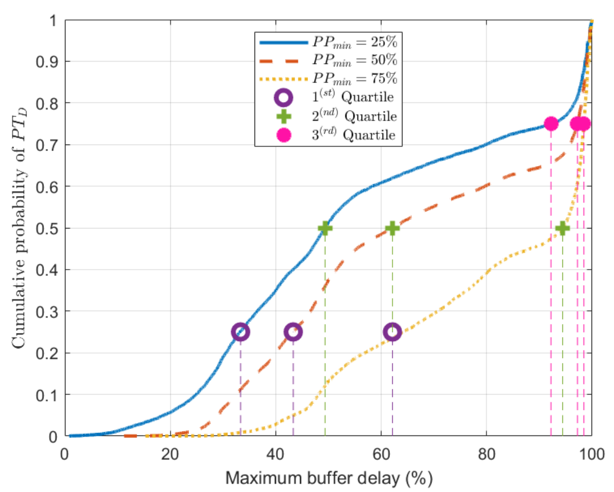

Fig. 5. Cumulative probability of maximum buffer delay PT_D for the optimal transmission window TW_O where the minimum power saving requirement PP_{min} is set to 25%, 50%, and 75%.

maximum buffer delay of less than 43% and 33% respectively. These are a significant number of gait (25% and 50%) which achieved a significant reduction of maximum buffer delay (at least 57% and 38% respectively) compared to G-TPC, for reasonable power savings requirement (PP_{min} = 50%).

IV. Conclusion

In this work, we investigated the properties of the WBAN channel between the wrist and the waist during walking for the purpose of improving the energy efficiency of the channel. More precisely we proposed a new approach based on the transmission window instead of transmission point, to reduce the maximum buffer delay for the G-TPC without effecting the power saving. The RSSI gait patterns of 20 subjects were investigated and the results show that the same power-saving achieved by G-TPC can be achieved with less than half of the maximum buffer delay 1.2% of the time. Also, the study indicated that with lenient power-saving requirements (PP_{min} = 50%), at least half of the gait channels can reduce the maximum buffer delay by more than a third.

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