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Channel Deviation-Based Power Control in Body Area Networks

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Abstract—Internet enabled body area networks (BANs) will form a core part of future remote health monitoring and Ambient Assisted Living (AAL) technology. In BAN applications, due to the dynamic nature of human activity, the off-body BAN channel can be prone to deep fading caused by body shadowing and multipath fading. Using this knowledge, we present some novel practical adaptive power control protocols based on the channel deviation to simultaneously prolong the lifetime of wearable devices and reduce outage probability. The proposed schemes are both flexible and relatively simple to implement on hardware platforms with constrained resources making them inherently suitable for BAN applications. We present the key algorithm parameters used to dynamically respond to the channel variation. This allows the algorithms to achieve a better energy efficiency and signal reliability in everyday usage scenarios such as those in which a person undertakes many different activities (e.g. sitting, walking, standing, etc). We also profile their performance against traditional, optimal and other existing schemes for which it is demonstrated that not only does the outage probability reduce significantly, but the proposed algorithms also save up to 35% average transmit power compared to the competing schemes.

Index Terms—Adaptive Power Control, Body Area Networks, IEEE 802.15.6, Transmission Power Control, Wearable Devices.

I. INTRODUCTION

The 21st century has witnessed a major evolution in the standard of living. Nonetheless, human beings still suffer from various challenges related to health. An ageing population in many developed countries is currently placing a strain on health care systems and incurring huge healthcare costs. For example, in the United Kingdom, life expectancy among people who are aged 65 and over has increased at an average rate of 1.2% per year for men and 0.7% for women over the last 30 years [1]. The public provision of health and social care is anticipated to account for one-fifth of the United Kingdom's entire GDP over the next 50 years, which is nearly 2.5 times greater than the current figure [2]. It is not just the elderly who are vulnerable, recently increasing numbers of people have been experiencing sudden deaths as a result of conditions such as stroke and heart attacks. This is partly due to an inherent lack of capability to detect and warn people

when the early symptoms of these diseases appear. Clearly, these problems motivate a scalable solution, which is able to pervasively connect people with doctors and to provide real time health monitoring.

Recently, body area networks (BANs) have been emerging as a key component to build AAL applications and remote health monitoring systems to assist both patients and their clinicians at a distance [3] [4]. In particular, patients are outfitted with a network consisting of tiny, wearable, low-power bio-sensors which are capable of recording biological data continuously. These intelligent sensors are responsible for collecting life vitals such as heart rate, electrocardiogram or even implanted inside body tissues to measure blood glucose or detect cardiovascular diseases [5]. Subsequently, this information can be sent to personal devices (cell phones, computers, etc) for visual display or reported to databases in medical clinics for proper diagnostics through a network connected to the cloud, which allows patients to engage in normal activities or undergo treatments in their own homes instead of staying in or close to hospitals [6]. It is anticipated that remote diagnostics and prompts for patients could save a significant amount of clinical interaction, time, and reduce the burden on national health services around the globe.

Already aware of the potential benefits of emerging BAN applications, significant effort has been put into the development of the IEEE 802.15.6 standard specified for low power, short range, and extremely reliable wireless communication within the surrounding area of the human body [7]. While the standard has accelerated research and development in the area, many challenges associated with BANs still remain. One of the most striking difficulties is a power control method which has not been completed yet in the context of the IEEE 802.15.6 standard. This is clearly a fundamental requirement in BANs [7] because computational power is limited for the constituent resource constrained nodes. In health monitoring applications, BAN devices are quite often in an active state on the patients' body to guarantee that vital signals are updated in a timely manner for further analysis and diagnostics; therefore, it is crucial for BAN nodes to be as energy efficient as possible to avoid constant recharging and replacement of batteries. Therefore, the focus of this paper is to propose practical transmission power control schemes to facilitate long-term, low-power operation and also improve the signal reliability for future BAN applications.

The main contributions of our work can be summarized as follows. **Firstly**, we begin by performing simultaneous measurements of the received signal strength of different on-

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body and off-body BAN links including chest-to-base station, wrist-to-base station and chest-to-wrist¹ links in various environments such as: an open office, outdoors and in a home environment. The data obtained illustrates that large variations in the signal strength can occur for all links and environments emphasizing that an effective power control mechanism is necessary for both saving energy and avoiding outage. Our **second** and most significant contribution is the proposal of 3 practical and novel power control methods. The first algorithm is a form of traditional adaptive power control mechanism with its key parameters kept constant. The second strategy is capable of updating the high threshold parameter based on the channel deviation while in the final scheme, the transmit power can be set for several time slots into the future. The proposed schemes are shown to be advantageous for wearable hardware platforms with limited CPU and memory resource, and also extremely flexible thanks to the different modes which can be set-up to achieve the desired trade-off between the energy efficiency and outage probability. **Finally**, we then benchmark our proposed algorithms based on field measurements obtained from realistic scenarios and illustrate that not only does the achieved performance exceed existing approaches available in the literature, it also satisfies the outage performance requirement of the IEEE 802.15.6 standard (i.e. the obtained outage probability is lower than 10%). We also analyze the energy efficiency and outage probability performance for each of the considered links and environments in order to provide guidelines on identifying the appropriate algorithm parameter settings relevant to the operating scenarios.

The remainder of this paper is organized as follows. Section II discusses some of the existing works relevant to the power control techniques proposed in this paper. A description of the measurement set-up and environments are provided in Section III. Section IV describes the characteristics of the channel data obtained from the field measurements. Section V provides an overview of the traditional adaptive power control method, while the novel practical transmit power control algorithms are proposed in Section VI. Their performance in all modes and scenarios is studied in Section VII. Finally, Section VIII summarizes our work.

II. RELATED WORKS

Transmit power control has been widely studied in the context of wireless sensor networks (WSNs) (see [8] and references therein). For example, in [9] a feedback control algorithm was proposed based on control-theoretic techniques that maintain a desired link quality by dynamically adjusting transmission power using online link quality measurements. In [10], the authors developed a linear prediction model to correct the receive signal strength indicator (RSSI) and transmission power level index after performing various measurements in different environments. These mechanisms, while useful, have focused primarily on static sensors in well defined environments. Obviously, their application to BANs, may not

guarantee optimum power saving and performance due to the diverse nature of human movements and environments in which they reside [11] [12].

More relevant to the novel algorithms proposed in this paper are the following power control methods. In [13] a simple adaptive algorithm was introduced to control the transmission power for an off-body system used for healthcare monitoring operating at 2.45 GHz. Specifically, feedback of the RSSI was used to adjust the transmit power in order to maintain the RSSI values within a range bounded by two levels, namely a low and high threshold. These two threshold levels were determined by performing numerous experimental activities which are typical of patient behavior within medical centers such as: normal walk, slow walk, and resting. The experimental traces indicated that high and low levels of -80 and -85 dBm respectively were appropriate for the platform being investigated. The algorithm was shown to save between 14–30% energy usage compared to simply using the maximum transmit power. A “sample-and-hold” algorithm was proposed in [14] which demonstrated that long-term channel prediction and adaptive power control is suitable for on-body BAN communications. While, in [15], a power control scheme for BAN communications based on differing body postures was presented. Using an empirical relationship between the power index and RSSI, the transceiver utilized the two most recent transmit powers and RSSI values to infer the postural position and compute the power level. A similar strategy was also applied in [10] for some well-defined environments (grass field, parking lot and corridor) in WSNs.

More recently, similar work was published in [16]. Therein, two methods were proposed to optimize the transmit power: short-term and long-term link-state estimations which enable the transceiver to adapt the transmission power level and target the RSSI threshold range to simultaneously satisfy the requirements of energy efficiency and link reliability. In [17] a predictor tuning algorithm was introduced which used a filter memory to adapt to the propagation conditions and subsequently to estimate fading conditions. Taking a different approach from the works discussed above, the author of [18] adopted a new approach: estimate the next channel sample based on the closest match in the past. In particular, an interval of 1000 samples (equivalent to 5 seconds) was used. The algorithm was programmed to predict 30 samples (150 ms) ahead of the last received sample by using the 970 channel gain samples that preceded it. While accurate, these approaches seem impractical for implementation on resource constrained BAN nodes as they require significant data processing to be performed on the device. Motivated by these observations, in the sequel we propose a number of new transmission power control strategies that are efficient, capable of being context-aware and dynamic, but most importantly, are relatively straight forward to implement.

III. MEASUREMENT SET-UP AND ENVIRONMENTS

A. Measurement Set-Up

In this study, two modes of BAN operation were considered, namely on-body BAN and off-body BAN. The on-body BAN

¹The chest-to-wrist link was chosen to emulate the case where a medical device forwards data to a smart watch which may be acting as an on-body base station.

Fig. 1. Illustration of the position of the 2 hypothetical BAN nodes, base station and 3 considered links: (a) chest-to-base station (b) wrist-to-base station and (c) chest-to-wrist.

Fig. 2. Pictures of the: (a) Measurement hardware (b) Open office environment (c) Outdoor environment and (d) Home environment.

operated between two nodes placed at the central-chest and right-wrist region of an adult made of height 1.67 m and mass 62 kg as illustrated in Fig. 1. This set up formed the chest-to-wrist link. Both BAN nodes were considered to avail of an off-body BAN mode of operation, where they could communicate with a nearby base station. These body worn node locations were selected as they are likely to be used in future BAN applications. For example, the chest region is a suitable location for monitoring electrocardiogram (ECG) whereas the wrist region is a possible location for a smart watch. For each body worn node, the transmit antenna was mounted tangentially with respect to the body surface of the test subject using a small strip of Velcro[®]. Each BAN node contained a controller radio board and a measurement radio board which could act as both transmitter and receiver. The measurement radio board was an ML5805, manufactured by RFMD, which was figured to operate at 5.8 GHz, as shown in Fig. 2(a). When working as a transmitter, the BAN node transmitted a continuous wave signal with an output power level of +17.6 dBm. Conversely, when functioning as a receiver, these nodes recorded the RSS using a 12-bit analogue-to-digital converter on the attached controller radio. The controller radio was a CC1110F32 Sub-1 GHz wireless microcontroller unit manufactured by Texas Instruments. It operated at 868 MHz, so as not to interfere with the main measurements, and was used for synchronizing the operation

Fig. 3. Received signal strength for the links: (a) Off-body: Chest-to-base station; (b) Off-body: Wrist-to-base station and (c) On-body: Chest-to-wrist in the open office environment.

of all of the hypothetical BAN nodes. It also determined whether the measurement radio operated as a transmitter or a receiver according to a time-slotted, round robin protocol. All information broadcasted by the controller radio on each node and the coordinator were centrally recorded by a base-station connected to a PC. Note that during any particular time slot, only one node could operate as a transmitter whereas the others worked as receivers and sampled the RSS. Moreover, each super frame was transmitted every 5 ms.

B. Environments

1) *Open Office*: The first set of measurements was conducted in an open office area with dimensions of 10.62 m $\times$ 12.23 m situated on the 1st floor of the Institute of Electronics, Communications and Information Technology (ECIT) building at Queen's University Belfast in the United Kingdom, as shown in Fig. 2(b). The open office area mainly consisted of PCs, metal storage units, chairs and desks constructed from medium density fibreboard. The desks were separated by vertical soft wooden partitions. The experiments were performed when the room was occupied to encapsulate as realistic operating conditions as possible. The base station was attached to a wall at a height of 2.4 m above the floor.

2) *Outdoor Environment*: The second set of measurements considered an outdoor area, namely a car park next to the ECIT building which contained a number of vehicles, as shown in Fig. 2(c). It should be noted that all of the channel measurements were performed during normal working hours and were therefore subject to perturbations caused by cars and the movement of nearby pedestrians. During the experiment, the base station was positioned at a height of 5.92 m above the ground level by attaching it to the side of the building.

3) *Home Environment*: The third set of measurements was performed on the 3rd floor of a typical terraced city dwelling as commonly seen in residential regions of the United

Fig. 4. Received signal strength for the links: (a) Off-body: Chest-to-base station; (b) Off-body: Wrist-to-base station and (c) On-body: Chest-to-wrist in the outdoor environment.

Kingdom. The measurement area consisted of a hallway, a room with dimensions of 5.0 m $\times$ 4.0 m and another room with dimensions of 3.5 m $\times$ 4.0 m. The hallway is 1.5 m wide and is adjacent to the stairs which connect the 2nd and 3rd floors. During the measurements, the hypothetical base station was located on a wall, at a height of 2.1 m above the floor in the hallway area and outside both of the rooms, as shown in the Fig. 2(d). This setting emulated remote health monitoring in a household environment. The majority of the test subject's activity took place in the larger room which consisted of typical furniture such as a bed, chair, desk and several electronic devices including a laptop, a television and a speaker. It is worth noting that the experiment was performed when the room was unoccupied except for the test subject.

C. Experiments

Each set of measurements was conducted for 3.5 minutes, enabling the collection of 40000 data samples for each link during each scenario. It is important to note that depending on the type of captured physiological signal, a high or low data sampling rate might be required. For instance, when using an accelerometer and gyroscope to capture acceleration and orientation during activities such as running, a high sampling rate is often required. On the contrary, some other physiological metrics such as body temperature will not change abruptly; therefore, occasional data sampling will suffice [19]. Although our sampling rate is sufficient for the majority of BAN applications, in this study we sub sampled our channel acquisitions to provide data sets with effective sampling periods of 150 ms. This sampling period was specifically chosen to objectify the study performed here and allow our results to be interpreted in the context of the IEEE 802.15.6 standard. The mean recorded noise floor in all 3 different environments was measured prior to the experiments and found to be approximately -102 dBm.

Fig. 5. Received signal strength for the links: (a) Off-body: Chest-to-base station; (b) Off-body: Wrist-to-base station and (c) On-body: Chest-to-wrist in the home environment.

IV. EXPERIMENTS AND SOME EMPIRICAL OBSERVATIONS OF LINK DYNAMICS

A. Open Office

During the measurement trials, the test subject initially worked at his desk for approximately 60 seconds. After this, the person stood up and walked randomly within the open office area for nearly 63 seconds. Following this, he stopped and stood stationary at an arbitrary position, before walking randomly again for the remainder of the measurement session. To illustrate the characteristics of the RSS obtained from the measurements, Fig. 3 shows the RSS for all links in the open office environment. Taking into account the noise threshold of the receiver used in this study (which is comparable to many commercially available RF chipsets used in BAN nodes) and the waveforms depicted in Fig. 3(a), the opportunity for using a dynamic power control mechanism is clearly evident. For example, assuming that the RSS must be at least 10 dB above the noise threshold to ensure successful signal detection and demodulation, it can be seen that lowering the transmit power by 30 dB during the standing period for the chest-to-base station and chest-to-wrist links would have no impact on outage. Regions where similar reductions and performance could be achieved for the other links can also be identified.

B. Outdoor Environment

The test subject started the measurements by standing at a location which was nearly 9 m away from the base station for approximately 60 seconds in the car park. Immediately following this, he walked randomly in the car park before stopping and standing at an arbitrary position. Afterwards, and similar to the measurements conducted in the open office area, the test subject continued to walk randomly during the rest of the measurement session. Fig. 4 presents the RSS for all links in the outdoor environment. In Fig. 4(a) we can see that: the RSS for the link chest-to-base station is fairly low (around

−70 dBm) for the first half of the walking phase due to the test subject is blocking the line-of-sight signal between the sensor on the chest and the base station. It then rises to a perceptibly higher value of −50 dBm in the second part of the period when the test subject is walking towards the base station. This walking phase reveals the shortcomings of using a fixed transmit power, namely a low transmit power level would result in weak received signal levels and outage during the first half, whereas a high transmit power level would unnecessarily waste energy in the latter half.

C. Home Environment

In this scenario, the test subject initially sat in the larger of the two rooms before going out and walking down stairs. This took approximately 123 seconds. Afterwards, he came back to the room and lay on the bed for approximately 50 seconds. After this, the test subject walked normally around the room for the rest of the measurements. Fig. 5 shows the RSS for all links in the home environment. Here, the RSS fluctuates significantly during the walking plus climbing periods. For the chest-to-base station and wrist-to-base station link, it reaches a peak of around −30 dBm due to the clear line-of-sight presented by the test subject walking towards the base station. In direct contrast, it occasionally declines to levels as low as −70 dBm when the test subject walked down the stairs while the RSS of the on-body link fluctuated significantly, regardless of the position of the test subject in the home environment.

It is important to highlight some common characteristics that can be observed from the obtained data. Firstly, among the 3 considered links, due to the dynamic nature of the test subject's wrist, most fluctuation of the RSS can be found in the wrist-to-base station link. Moreover, two different characteristic can be observed from the figures: (1) the RSS fluctuates significantly and unpredictably during dynamic periods (walking, climbing), which means that the power control algorithm must be capable of adapting to the transmit power quickly to the rapid changes of the channel; (2) the RSS is relatively stable during static periods (standing, sitting, lying), which shows potential opportunity for energy savings and permits the power control algorithm to slowly adapt to the channel as suggested in [14]. Having achieved an understanding of the channel characteristics of different links in various operating scenarios, the next sections propose some novel adaptive transmit power control algorithms specifically for BAN applications.

V. AN OVERVIEW OF ADAPTIVE POWER CONTROL

A. Adaptive Power Control - A Discussion

In general, most adaptive power control methods [13] [15] [16] [17] attempt to keep the RSSI (or the RSS) within a region bounded by two important parameters, namely high (T_H) and low threshold (T_L) with $T_L \leq T_H$. In particular, the T_L value should be high enough to assure that the RSS is greater than the receive sensitivity to avoid outages, whereas the T_H is responsible for saving energy.

In this work let $RSS(i)$ denote the RSS information fed back from the receiver at time slot i and $RSS(n)$ stand for the current RSS information. Here, we concentrate on varied

Fig. 6. The probability that the next channel gain falls into the deviation domain with various values of α and sampling periods while the test subject is walking in the open office.

amounts of compensation, which are denoted by $x(n)$ in case $RSS(n)$ is below T_L and $y(n)$ in case $RSS(n)$ is above T_H . Such cases normally occur when the $RSS(n)$ suddenly experiences a dramatically unstable channel quality due to the multipath fading and body shadowing caused by human body blockage, obstruction by surrounding obstacles [11] or a combination of all three. Let's consider the value of $x(n)$ and $y(n)$ required to simultaneously prevent the next RSS, or $RSS(n+1)$ from outage and conserve transmit power as well. Let $P(i)$ and $h(i)$ denote the transmit power used and the channel gain in the time slot i . Note that the units associated with the parameters in our work are dB and dBm. There are three cases of key interest which can occur as the RSS evolves over time, these are:

- $T_L \leq RSS(n) \leq T_H$: In this case, the channel quality has not changed significantly in the current time slot compared with the previous one [i.e. $RSS(n-1)$]. The transmit power will remain unchanged in the forthcoming time slot [13] [16], or simply $P(n+1) = P(n)$.
- $RSS(n) < T_L$: This case implies that in the time slot n the channel quality has deteriorated compared to $RSS(n-1)$. Hence, to avoid outage the transmit energy for the time slot $n+1$ should be increased by an amount equal to $x(n)$ computed in the time slot n , or

$$P(n+1) = P(n) + x(n) \quad (1)$$

- $RSS(n) > T_H$: This case occurs when the channel quality has improved so that the RSS now resides in the region above T_H . Therefore, the transmit power for the forthcoming time slot should be reduced by an amount equal to $y(n)$ computed in the time slot n , in order to save energy

$$P(n+1) = P(n) - y(n) \quad (2)$$

Now let's focus on the latter two scenarios. The most critical and hence prioritized condition is guaranteeing that $RSS(n+1)$ is higher than the low threshold in both cases, which means

$$RSS(n+1) = P(n+1) + h(n+1) \geq T_L \quad (3)$$

Fig. 7. Channel gains (a) and the corresponding deviation values with $N = 10$ (b) for the off-body link: chest-to-base station in the home environment.

B. The Domain of the Forthcoming Channel Gain

From the inequalities (1), (2) and (3), to calculate appropriate values for $x(n)$ and $y(n)$, we need to know the value of $h(n+1)$ which is clearly not available in current time slot. In this work, we adopt an approach using knowledge of the channel deviation to predict the range of the next channel realization and recognize how rapidly the channel fluctuates. It is proposed that the standard deviation of the previous N channel data samples, denoted as $\sigma(n)$ (dB) is calculated according to

$$\sigma(n)^2 = \frac{1}{N-1} \sum_{i=0}^{N-1} (h(n-i) - \Delta)^2 \quad (4)$$

where Δ is the mean of these N channel gains.

Fig. 7 illustrates the relationship between the channel gain and its corresponding standard deviation as the person participated in various activities which are common in a household environment such as stair climbing, sitting and lying, etc. During the stable periods (e.g. the interval 0–400), the channel can be seen to experience low deviations of less than 1 dB. Conversely, the deep fades which occur around the time slot² 700 result in a rapid deterioration of the channel and as a consequence, a larger deviation value is observed (approaching 12 dB). The deviation partly reflects the difference between $h(n)$ and $h(n+1)$, for example, they are similar when the channel is stable [i.e. $\sigma(n) \rightarrow 0$] however, when the channel changes significantly [e.g. $\sigma(n) \gg 5$ dB] the difference between proximate channel realizations can be considerable.

Due to the rapidly changing channel deviations which can occur and inspired by the three sigma rule [20], we consider the use of a pre-defined tuning parameter, α , which is used to adjust the domain of the forthcoming channel gain $h(n+1)$. Put simply, this is a constant applied to the channel deviation, i.e. $\alpha\sigma(n)$, to adjust the range of channel realizations which can be accommodated by our power control strategy. Herein we refer to this region as the *deviation domain*. To illustrate this concept, Fig. 6 shows the probability that $-\alpha\sigma(n) \leq$

$h(n+1) - h(n) \leq \alpha\sigma(n)$ for $0 \leq \alpha \leq 3$ for all links with the data obtained in the home environment. As we can see, between 60 and 70% of all forthcoming channel gains remain within one deviation of the current one (i.e. $\alpha = 1$) while almost all of the forthcoming channel gains (83%) reside within 2 deviations from the current one (i.e. $\alpha = 2$). By setting $\alpha = 3$, ensures that approximately 95% of the forthcoming channel gains fall into the deviation domain. A similar trend can also be identified for all links in the remaining scenarios. Clearly the choice of α will have a significant impact on the energy saving and outage performance of BAN nodes. This will be discussed in more detail in the next section.

VI. SOME PRACTICAL TRANSMIT POWER CONTROL ALGORITHMS

A. Fixed Transmit Power Control Algorithm (Algorithm 1)

The first algorithm focuses on how to compensate the transmit power to guarantee that $RSS(n+1)$ stays above T_L for every case that the next channel gain falls into the deviation domain. For the case that the current RSS is below T_L , then from the inequalities (1 and 3), to ensure that the forthcoming RSS is above the low threshold we have $P(n) + x(n) + h(n+1) \geq T_L$. Since $P(n) = RSS(n) - h(n)$, then $x(n) \geq T_L + [h(n) - h(n+1)] - RSS(n)$. To guarantee this condition always occurs and that the next channel gain falls into the deviation domain, we must have

$$x(n) \geq \max \{T_L - RSS(n) + [h(n) - h(n+1)]\} \quad (5)$$

By changing the inequality to equality, then we have the solution

$$x(n) = T_L - RSS(n) + \alpha\sigma(n) \quad (6)$$

For the case that the current RSS is above T_H , then by following similar transformations, the condition for $y(n)$ can be obtained as $y(n) \leq RSS(n) - \alpha\sigma(n) - T_L$.

It should be noted that the quantity $RSS(n) - \alpha\sigma(n) - T_L$ is not always greater than 0 (e.g. the channel fluctuates dramatically, then the dispersion covers the whole of the targeted area). Therefore, our solution turns to be

$$y(n) = \max \{0, RSS(n) - \alpha\sigma(n) - T_L\} \quad (7)$$

This equation indicates that in the case where the channel varies dramatically, the transmit power should remain unchanged to avoid outage in the next time slot.

The proposed adaptive power control scheme is outlined in Algorithm 1. We note that in step 2 and 3, $P(i+1)$ will be set to the maximum / minimum power if it reaches higher / lower than the maximum / minimum allowable power. As we can see, because of its simple form, the algorithm is fairly straightforward to implement on platforms with very limited CPU and memory resources because the majority of the computational calculations are based on addition and subtraction. The most complicated section corresponds to calculating the deviation value. This can readily be achieved using existing algorithms such as the *two-pass algorithm* (for the case when N is small [21]), or using the *on-line algorithm* which is widely applied to hardware with limited memory

²We consider each channel sample as representing a hypothetical time slot.

Algorithm 1: Fixed Power Control Algorithm

Inputs : $RSS(i)$
Givens : T_H, T_L, α, N
Outputs: $P(i+1)$
1) % Calculate the channel gains and the deviation for each time slot
Compute $h(i) \leftarrow RSS(i) - P(i)$
Compute $\sigma(i)$
2) **If** $RSS(i) < T_L$ **then**
 $P(i+1) = P(i) + (T_L - RSS(i) + \alpha\sigma(i))$
3) **Else if** $RSS(i) > T_H$ **then**
 $P(i+1) = P(i) - \max\{0, RSS(i) - \alpha\sigma(i) - T_L\}$
4) **If** $T_L \leq RSS(i) \leq T_H$ **then**
% No further action
5) **End if**

storage [22]. Since the chosen value of N will typically be low (e.g. 10 – 20 samples), both approaches are suitable for the practical implementation of the proposed Algorithm 1.

It is worth highlighting that the proposed power control scheme is less complex than the methods introduced in [17], which utilized the minimum least square error estimator, [16], which used long-term link-state estimation and [18] which adopted a channel prediction mechanism. Compared with the reactive power control in [13], it appears slightly more complex; nonetheless, increasing multiplicatively or decreasing additively the transmit power by a constant level [13] is somewhat less effective than the approach proposed here because it is extremely slow for the algorithm to adapt to the channel when it deteriorates or improves rapidly. Moreover, while we have considered the RSS in the development of the algorithm proposed here, it is readily transferable to applications which consider RSSI or SINR estimated from RSSI [23].

As well as its computational simplicity, the proposed algorithm is also extremely flexible since the α parameter allows it to be tuned for an appropriate trade-off between energy efficiency and outage probability. As one might insinuate from the algorithm, increasing α will lead to a better outage performance with more transmit energy sacrificed. Obviously, increasing α could raise $x(n)$, but reduce $y(n)$; hence, it emphasizes link conservation more than saving energy. Based on this, three modes can be set up for different practical applications. For example, a relatively low value α could be used (e.g. $\alpha = 1$) so that a low RSS value triggers a narrow *deviation domain* or an *aggressive* power saving mode. Besides, a *conservative* strategy which emphasizes the outage performance more than saving energy could be activated by setting up a higher value α (e.g. $\alpha = 2$) which enlarges the *deviation domain*. Similarly, one may set a more *balanced* mode which targets both energy saving and outage by setting $\alpha = 1.5$. The performance of the power control scheme for specific parameter settings and different modes is discussed in Section VII.

Algorithm 2: Dynamic Power Control Algorithm

Inputs : $RSS(i)$
Givens : T_L, α, N
Outputs: $P(i+1)$
1) % Calculate the channel gains and the deviation for each time slot
Compute $h(i) \leftarrow RSS(i) - P(i)$
Compute $\sigma(i)$
2) % Update the high threshold value
Compute $T_H(i) = T_L + \alpha\sigma(i)$
3) **If** $RSS(i) < T_L$ **then**
 $P(i+1) = P(i) + (T_H(i) - RSS(i))$
4) **Else if** $RSS(i) > T_H(i)$ **then**
 $P(i+1) = P(i) - (RSS(i) - T_H(i))$
5) **If** $T_L \leq RSS(i) \leq T_H(i)$ **then**
% No further action
6) **End if**

B. Dynamic Transmit Power Control Algorithm (Algorithm 2)

It is important to note that the necessary condition required to avoid outage is guaranteeing that the forthcoming RSS is above the low threshold as can be seen in (3). However, in order to achieve better energy efficiency, the relationship between $RSS(n+1)$ and the high threshold should also be considered. Now focusing on the case when the forthcoming channel gain improves significantly in the next time slot (i.e. $h(n+1) \gg h(n)$), obviously an opportunity will exist to make energy savings since the channel has just improved. In this case, the RSS at time slot $n+1$ will be greater than T_H and the following inequality will be satisfied

$$RSS(n+1) = P(n+1) + h(n+1) \geq T_H \quad (8)$$

From the formulation given in (6), (8) can be re-written as

$$T_L + \alpha\sigma(n) + [h(n+1) - h(n)] \geq T_H \quad (9)$$

To ensure that (8) always holds true, the following condition should be satisfied $T_L + \alpha\sigma(n) \geq T_H$. By executing the same manipulation for the case when $RSS(n) \geq T_H$, a similar result is obtained. In general, the closer T_H stays to T_L , the more likely that the RSS could go into outage when the channel fluctuates rapidly. Hence, we choose $T_H - T_L = \alpha\sigma(n)$. This equation suggests that the difference between the two threshold values, or the width of the targeted area should be equal to the amount of dispersion in the channel.

Following from this, the high threshold T_H can be dynamically updated at each time slot as $T_H(n) = T_L + \alpha\sigma_n$. The proposed dynamic algorithm is outlined in Algorithm 2. It should be noted that, now $x(n) = T_H(n) - RSS(n)$ and $y(n) = RSS(n) - T_H(n)$. As can be seen, Algorithm 2 is of a relatively low-complexity, and therefore will be straightforward to implement, even on resource constrained hardware such as BAN nodes. Similar to the Algorithm 1, it is also very flexible since the parameter α can be tuned for the three modes. Clearly, when the channel is quite stable (e.g. the user is standing stationary, resting, sleeping etc.), $\sigma(n) \approx 0$ or equivalently $T_H \approx T_L$ irrespective of the value

Algorithm 3: Sample-and-hold Power Control Algorithm

Inputs : $RSS(i)$
Givens : $T_L, \alpha, N, B_{min} = 0, B_{max}$
Outputs: $P(i+1 : i+B)$
1) % Checking the deviation $\sigma(i)$ based on the feedback
2) **If** $\sigma(i) < 2$ **then**
Increase B by a constant
3) **Else**
 $B = B/2$
4) **End if**
5) Compute the transmit power by using the dynamic algorithm
6) % Hold for B time slots
 $P(i+1 : i+B) = P(i)$
7) After these B time slots, jump back to step 1.

of α . In this instance, the scheme will keep the transmit power as low as possible for energy conservation. In contrast, when the channel varies rapidly, i.e. the user is more active (e.g. walking fast or running), the channel will deviate with much greater values of $\sigma(n)$. Hence the maximum transmit power will be used in this case so as to avoid outages. Furthermore, regarding the performance, since the dynamic algorithm is also designed to satisfy condition (3) to avoid outages, an identical outage probability performance to the fixed algorithm is to be expected.

C. Sample-and-hold Power Control Algorithm (Algorithm 3)

Due to the frequent episodes of long-term temporal stability which can be encountered in BAN channels, a simple sample-and-hold power control is introduced in Algorithm 3. In particular, this strategy allows the transmitter node to broadcast its signal at a specific power level for a pre-calculated interval, which may last for several superframes (i.e. multiple timeslots) depending on the channel deviation. It is anticipated that adopting this type of approach will decrease the working load of the transmitter, particularly when the channel undergoes extended periods of relative stability. Note that this scheme utilizes the dynamic power control algorithm as a baseline.

As we can see in Algorithm 3, the transmit power is held constant during a back-off period equal to B time slots which is bounded by its minimum and maximum allowable values (B_{min} and B_{max}). Specifically, this back-off parameter is dynamically adjusted by analyzing the channel status. If the channel is temporarily static ($\sigma(i) < 2$)³, the back-off period will be increased by a constant (e.g. $B = B+2$), which means the transmit power will be held for 2 more time slots. If, on the other hand, the channel is fluctuating significantly ($\sigma(i) \geq 2$), the back-off period will be reduced multiplicatively and return quickly to the case where the transmit power is updated at each time slot. We emphasize the point that during the back-off period, the decrease in the transmit power is multiplicative while the increase is additive. Therefore Algorithm 3 has a clear bias towards reacting faster to a fluctuating channel than a stable one.

³This threshold is chosen based on the observation of the channel deviation obtained from the measurements.

TABLE I
PARAMETERS SET-UP

Parameters	Value
α	1; 1.5; 2.0
High Threshold (T_H)	-80 dBm
Low Threshold (T_L)	-87 dBm
Minimum Transmit Power (P_{min})	-25 dBm
Maximum Transmit Power (P_{max})	0 dBm
Number of Channel Samples considered (N)	10
Noise Threshold	-92 dBm
Sampling Period (SP)	150 ms
Minimum Back-off Period (B_{min})	0 time slot
Maximum Back-off Period (B_{max})	100 time slots

VII. AN ANALYSIS OF THE PERFORMANCE OF THE PROPOSED ALGORITHMS

In this section, using the channel data obtained from the scenarios described in Section III, we empirically evaluate the average transmit power for each transmission and the associated outage probability achieved while using the proposed algorithms. As a benchmark, we also compare their performance with the following algorithms: (1) **Optimal power transmission:** Defined as the lowest allowable transmit power at which the RSS at the receiver side is not lower than the low threshold, or $P_{opt}(i) = \max\{\min\{TL - h(i), P_{max}\}, P_{min}\}$; (2) **Constant power transmission:** A constant transmit power of -10 dBm is deployed for data transmission; (3) **Maximum power transmission:** The maximum transmit power of 0 dBm is deployed for data transmission; (4) **Reactive power control scheme:** The power control scheme proposed in [13] with 3 modes: *conservative*, *balanced* and *aggressive* mode; (5) **Long-term link-state estimation power control (LTLSE):** The power control scheme proposed in [16].

To allow a fair comparison between the algorithms listed above, the parameters in the Table I were used for all of the transmit power control schemes. All IEEE 802.15.6 standards compliant devices must use a maximum allowed transmit power $P_{max} = 0$ dBm [14]. For the purposes of evaluation, *outage* was defined as an event which occurs whenever the RSS at the receiver side is below a given noise threshold of -92 dBm. The low threshold was selected by adding a margin of 5 dB to the noise threshold. In our simulations we assume perfect channel state information is available from the receiver.

A. The Performance of Algorithm 1

Fig. 8 shows the utilized transmit power and the corresponding RSS for the chest-to-base station link under Algorithm 1 in the outdoor environment with $\alpha = 2.0$. As we can see, the algorithm attempts to keep the RSS within the -87 and -80 dBm threshold levels; however, occasionally it resides outside of these boundaries due to the rapid fluctuation of the channel while the person was walking. Moreover, when deep fading occurs (e.g. around time slot 600), the algorithm immediately ramps up the transmit power to compensate for the deterioration in the link quality whereas when the channel is reasonably stable (while the person was sitting or standing e.g. in the interval 0 – 400 and 800 – 1200), the scheme keeps the transmit power stable as well.

TABLE II
BENCHMARKS OF THE CONSIDERED TRANSMIT POWER SCHEMES IN THE OPEN OFFICE ENVIRONMENT

SCHEMES		Chest-to-base station		Wrist-to-base station		Chest-to-wrist	
		Av. Power(dBm)	Av. Outage(%)	Av. Power(dBm)	Av. Outage(%)	Av. Power(dBm)	Av. Outage(%)
Optimal		-20.9	0.2	-15.8	0.2	-24.3	0.0
Maximum 0 dBm		0.0	0.2	0.0	0.2	0.0	0.0
Constant -10.0 dBm		-10.0	1.1	-10.0	19.9	-10.0	0.1
LTLSE [16]		-17.8	2.3	-13.1	3.6	-22.6	2.3
Reactive Scheme [13]	Aggressive	-19.1	6.2	-14.2	6.3	-23.6	2.7
	Balanced	-18.8	5.6	-13.5	5.3	-23.2	2.4
	Conservative	-16.8	3.1	-12.6	3.3	-22.7	2.1
Fixed Algorithm	$\alpha = 1.0$	-18.5	2.3	-13.1	3.2	-23.2	1.8
	$\alpha = 1.5$	-17.9	1.9	-12.3	2.3	-22.9	1.4
	$\alpha = 2.0$	-17.3	1.7	-11.7	2.2	-22.2	1.3

TABLE III
BENCHMARKS OF THE CONSIDERED TRANSMIT POWER SCHEMES IN THE OUTDOOR ENVIRONMENT

SCHEMES		Chest-to-base station		Wrist-to-base station		Chest-to-wrist	
		Av. Power(dBm)	Av. Outage(%)	Av. Power(dBm)	Av. Outage(%)	Av. Power(dBm)	Av. Outage(%)
Optimal		-9.7	1.3	-3.5	7.6	-14.5	1.0
Maximum 0 dBm		0.0	1.3	0.0	7.6	0.0	1.0
Constant -10.0 dBm		-10.0	72	-10.0	14.9	-10.0	6.7
LTLSE [16]		-7.1	2.2	-0.9	8.0	-10.3	3.2
Reactive Scheme [13]	Aggressive	-7.0	4.7	-1.31	9.6	-12	8.3
	Balanced	-6.2	3.0	-0.7	8.3	-11	6.3
	Conservative	-5.8	2.1	-0.4	7.7	-9.6	4.8
Fixed Algorithm	$\alpha = 1.0$	-6.7	2.1	-1.3	8.6	-11	4.2
	$\alpha = 1.5$	-7.2	1.8	-0.9	7.9	-10.2	3.1
	$\alpha = 2.0$	-6.4	1.6	-0.6	7.6	-9.3	2.1

TABLE IV
BENCHMARKS OF THE CONSIDERED TRANSMIT POWER SCHEMES IN THE HOME ENVIRONMENT

SCHEMES		Chest-to-base station		Wrist-to-base station		Chest-to-wrist	
		Av. Power(dBm)	Av. Outage(%)	Av. Power(dBm)	Av. Outage(%)	Av. Power(dBm)	Av. Outage(%)
Optimal		-11.3	0.5	-13.4	1.1	-20.6	0.1
Maximum 0 dBm		0.0	0.5	0.0	1.1	0.0	0.1
Constant -10.0 dBm		-10.0	23.9	-10.0	32.4	-10.0	1.6
LTLSE [16]		-7.9	3.4	-10.5	3.9	-17.9	3.1
Reactive Scheme [13]	Aggressive	-8.5	6.7	-12.4	9.0	-19.4	6.9
	Balanced	-7.5	4.3	-11.8	7.0	-18.4	4.1
	Conservative	-6.6	3.8	-9.9	4.9	-17.5	3.0
Fixed Algorithm	$\alpha = 1.0$	-7.7	3.9	-10.3	4.6	-18.0	2.7
	$\alpha = 1.5$	-7.2	2.5	-9.0	3.1	-16.7	1.9
	$\alpha = 2.0$	-6.8	2.2	-9.1	2.6	-16.5	1.3

Fig. 8. The transmit power, RSS under Algorithm 1, optimal transmit power and channel data for the off-body link: chest-to-base station in the home environment with $\alpha = 2.0$.

The average power draw per transmission, as well as outage probability, for each of the schemes, are summarized in the Tables II, III and IV. For the open office environment, Algorithm 1 (with $\alpha = 1.0$) yields a relatively good signal reliability (average outage of 2.3%) with an average of -18.5 dBm

utilized for each transmission in the chest-to-base station link. Transforming the average transmit power to mW, the figure is nearly 50% above the optimal scheme, but 15% below the LTLSE scheme. The reactive scheme has a fairly low average transmit power for all links in all modes, but sacrifices up to more than 3% of the transmissions for the outage in the off-body links. Nonetheless, in all scenarios, it is clear that even greater power savings could be achieved by further sacrificing signal reliability. Moreover, it can be seen that the transmit power spent for the chest-to-wrist link is the least among 3 links due to the shortest distance between the chest and the wrist. For instance, the average transmission power of approximately -23.2 dBm (just slightly higher than the minimum transmit power $P_{min} = -25$ dBm) is sufficient to achieve a very low outage probability (just 0.018).

A similar trend can also be seen for the data in the outdoor environment. It is worth noting that while utilizing the constant transmit power of -10 dBm all links experienced significant outage (e.g. up to 72% for the chest-to-base station link and 14.9% for the wrist-to-base station link). This emphasizes the necessity of a power control algorithm in the context of BANs. In comparison, the average outage probability achieved while using the maximum transmit power (0 dBm) is as low as the figures obtained from the optimal scheme. Nevertheless,

Fig. 9. Color map of the average transmit power for Algorithm 1 with various thresholds for the wrist-to-base station link in the outdoor environment with $\alpha = 1.5$.

Fig. 10. Color map of the outage probability for Algorithm 1 with various thresholds for the wrist-to-base station link in the outdoor environment with $\alpha = 1.5$.

there is a huge expense in transmit power since 0 dBm is much higher than the mean transmit powers obtained using the other power control schemes. Meanwhile, although the LTLSE and fixed algorithm show a comparable performance for both the wrist-to-base station and chest-to-wrist links, the latter ($\alpha = 1.5$) still demonstrates a slightly better outage probability than the former (1.8% compared to 2.2%). For the home environment, both the LTLSE and fixed algorithm ($\alpha = 1.0$) utilize around -18 dBm for the on-body communications; however, the fixed algorithm obtains a slightly better outage probability (2.7% compared to 3.1%). Meanwhile the reactive scheme uses a lower average transmission power (-19.4 dBm); nevertheless, it experiences a fairly low outage probability, just 6.9%.

To highlight the importance of selecting the correct threshold levels, we also investigated the performance of Algorithm 1 for a range of T_H and T_L values between $[-90, -70]$ dBm. Fig. 9 illustrates the relationship between the average transmit power and the threshold values. When contrasting it with Fig. 10 which shows the outage probability, it represents a trade-off between the energy efficiency and outage probability:

- *Case 1: Low average transmit power (-3 to -1.75 dBm).*

Fig. 11. Transmit power, optimal transmit power, channel data and T_L , T_H values for the chest-to-wrist link in the outdoor environment with $\alpha = 2.0$.

Fig. 12. The transmit power, optimal transmit power, channel data and RSS for the wrist-to-base station link in the office environment with $\alpha = 2.0$.

This relates to the bottom left corner of Fig. 9 where $T_L \leq -87$ and $T_H \leq -81$. The corresponding region in Fig. 10 suffers from more than 0.09 of outage.

- *Case 2: Medium average transmit power (-1.75 to -1 dBm).* This corresponds to the central region of Fig. 9 where $-87 \leq T_L \leq -85$ and $-81 \leq T_H \leq -74$ with 8 to 9% of the transmissions in outage (Fig. 10).
- *Case 3: High average transmit power (-1 to 0 dBm).* This corresponds to the upper part of Fig. 9 with lower levels of outage (less than 0.08). In this case the T_L value is higher than -85 dBm and T_H is higher than -74 dBm.

Both figures show that the selected threshold values have a discernible impact on outage probability and power efficiency since increasing one (while fixing the other) will reduce outage but increase transmit power, and vice versa. Unfortunately, it is still difficult to determine the optimal values for the settings because each specific scenario requires different optimal thresholds. However, the results do emphasize that updating the algorithm parameters will be beneficial, especially when the channel is subject to significant variations.

TABLE V
BENCHMARKS OF THE DYNAMIC AND SAMPLE-AND-HOLD ALGORITHM IN THE OPEN OFFICE, OUTDOOR AND HOME ENVIRONMENT

ENVIRONMENTS	SCHEMES	α	Chest-to-base station		Wrist-to-base station		Chest-to-wrist	
			Av. Power(dBm)	Av. Outage(%)	Av. Power(dBm)	Av. Outage(%)	Av. Power(dBm)	Av. Outage(%)
Open Office	Dynamic Scheme	$\alpha = 1.0$	-19.6	2.4	-14.2	3.3	-23.7	1.8
		$\alpha = 1.5$	-19.1	1.9	-13.5	2.3	-23.3	1.4
		$\alpha = 2.0$	-18.6	1.7	-12.7	2.2	-22.8	1.3
	Sample-And-Hold	$\alpha = 1.0$	-19.5	2.6	-14.5	5.7	-23.8	1.8
		$\alpha = 1.5$	-19	2.2	-13.8	4.5	-23.4	1.4
		$\alpha = 2.0$	-18.4	2.0	-13.2	4.4	-22.9	1.3
Outdoor	Dynamic Scheme	$\alpha = 1.0$	-8.6	2.3	-1.9	8.8	-12.2	4.2
		$\alpha = 1.5$	-8.1	2.0	-1.4	7.9	-11.3	3
		$\alpha = 2.0$	-7.8	1.6	-1	7.6	-10.4	2.2
	Sample-And-Hold	$\alpha = 1.0$	-9.0	4.3	-2.0	9.7	-12.5	6.3
		$\alpha = 1.5$	-8.7	3.9	-1.5	8.7	-11.6	5.2
		$\alpha = 2.0$	-8.2	3.3	-1.1	8.3	-10.8	4.1
Home	Dynamic Scheme	$\alpha = 1.0$	-9.7	3.9	-11.6	4.6	-19.0	2.8
		$\alpha = 1.5$	-8.9	2.6	-10.9	3.2	-18.0	1.9
		$\alpha = 2.0$	-8.2	2.3	-10.2	2.6	-17.1	1.4
	Sample-And-Hold	$\alpha = 1.0$	-9.8	4.7	-11.7	5.0	-19.2	4.8
		$\alpha = 1.5$	-9.0	3.4	-10.9	3.9	-18.4	3.5
		$\alpha = 2.0$	-8.3	3.1	-10.3	3.3	-17.7	3.5

B. The Performance of Algorithm 2

Fig. 11 shows the transmit power and the threshold values for the on-body chest-to-wrist link in the outdoor scenario. The transmit power for Algorithm 2 can be seen to be quite close to the optimal one in which it occasionally reaches the maximum power when deep fading occurs (e.g. in the interval 500 – 800). During this period, the targeted area bounded by the two threshold values is enlarged to avoid outage. In comparison, during the stable period of movements (e.g. in the interval 800 – 1200) the transmit power under the dynamic algorithm is virtually identical to the optimal one. Accordingly, in these periods, the high threshold is updated to be quite close the low threshold to save energy.

The average power draw per transmission, as well as the outage probability, for Algorithm 2 under the different scenarios, are summarized in Table V. As expected, the dynamic algorithm exhibits a similar outage probability performance to that of the Algorithm 1 in most of the scenarios; however, the amount of energy saved is much greater. In particular, for the open office environment, with $\alpha = 1.5$, Algorithm 2 only utilizes around -19.1, -13.5 and -23.3 dBm for each transmission in the chest-to-base station, wrist-to-base station, and chest-to-wrist links, respectively, which is 24%, 24% and 8% below the average for the fixed algorithm. Compared with the LTLSE scheme, the dynamic algorithm uses 25% less energy for off-body communications and nearly 15% less for on-body communications. In the outdoor environment and targeting an aggressive mode of operation ($\alpha = 1.0$), the average amount of transmit power consumed by Algorithm 2 for on-body communications is approximately -12.2 dBm, which is 35% below the LTSLE algorithm (-10.3 dBm). The corresponding figures are 29.2% and 20% for chest-to-base station link and wrist-to-base station link respectively.

It is also worth noting that Algorithm 2 spends much less energy per transmission than Algorithm 1 since it is able to adapt the high threshold to the channel variation within each time slot. Over all algorithms and scenarios studied so far, this is to be largely expected since the signal received by the node positioned on the wrist has the tendency to fluctuate more frequently and severely than the one positioned

Fig. 13. Average transmit power (AP) and outage probability (OP) for various settings of the α parameter under the sample-and-hold algorithm (Algorithm 3) in the open office environment with different communication scenarios.

on the chest due to the oscillatory movement at the side of the person's body. Another interesting observation is that for all of the considered links, the average energy spent while transmitting in the outdoor environment was the highest while the lowest figure was found in the open office environment. This result suggests that the surrounding environment has a great influence on the energy conservation performance of the power control algorithms studied here.

C. The Performance of Algorithm 3

Fig. 12 shows the transmit power and the RSS under the sample-and-hold algorithm for the wrist-to-base station link in the open office environment. Because a constant level of transmit power is used for several time slots whenever a stable channel period is recognized, the algorithm may not respond as quickly to rapid changes in the channel compared to Algorithm 2. For instance, when the channel suddenly ramps up, in the region around the time slot 450, the transmit power remains unchanged at approximately -5 dBm, which is substantially

higher than the optimal one. Once again, in the case when the channel experiences spontaneous fading events, such as that experienced around time slot 1200, the slow reaction of the algorithm causes the RSS to fall into outage. When substantial changes in the channel occur, Algorithm 3 takes between 1 and 6 time slots to respond which is slower than the dynamic algorithm, but fairly quick for most sample-and-hold algorithms. The scheme then continues to adjust the transmit power according to the channel state within each time slot, which can obviously be seen in the time interval (450 – 800).

The average power draw per transmission, as well as the outage probability, for the sample-and-hold algorithm under the different scenarios, are summarized in Table V. Because the transmitter is allowed to transmit constantly for a maximum 100 time slots, it could be slower in adapting to rapid changes of the channel, leading to a significant degradation in the signal reliability compared with the case that the transmission power and the high threshold are updated each time slot (i.e. Algorithm 2). For instance, in the open office environment, with $\alpha = 1.0$, 5.7% of the received signals level were in outage for the wrist-to-base station link, which is higher than that for the dynamic scheme. When it comes to the outdoor and home environment, the outage probability achieved from the sample-and-hold algorithm is also degraded in comparison with Algorithm 2. In particular, in the outdoor environment, the outage probability achieved when setting $\alpha = 2.0$ and $\alpha = 1.0$ is 4.1% and 6.3%, respectively. In the home environment, the corresponding figures are 3.5% and 4.8%. However, it can be clearly seen that in most cases the sample-and-hold algorithm experiences considerably less than 10% outage, which meets the requirement specified in the IEEE 802.15.6 standard.

D. Tuning the Parameters

Before concluding this section, we take the opportunity to highlight the impact of the algorithm parameter α on the performance of Algorithm 3.⁴ Fig. 13 plots the transmit power per transmission (right ordinate) and outage probability (left ordinate) of the sample-and-hold algorithm for various α value for different scenarios in the open office. In general, as α is increased, the outage performance improves with a greater average transmit power being used in all the scenarios. A trade-off between the outage probability and transmission power can be found in the figure where three regions / modes can be identified, namely: *aggressive*, where $\alpha \leq 1$; *balanced*, where $1 < \alpha < 2$; and *conservative*, where $\alpha \geq 2$. For the open office environment, all modes achieved an outage probability of less than 10%. The highest figures are witnessed for the wrist-to-base station link in the aggressive mode, which ranges from 5.8% ($\alpha = 1$) to 9.6% ($\alpha = 0$) of outage. Although not shown due to space limitation, a worse performance was obtained in the outdoor scenario where the outage probability of the wrist-to-base station and chest-to-wrist link occasionally exceeds 10%. In particular, from 9.7% to 14.2% of all wrist-to-base station links were in outage when the aggressive mode was active. The corresponding figures

for chest-to-wrist links are 6.3% to 11%. Regarding the home scenario, the aggressive mode guarantees between 5% to 9.2% of all RSS levels were determined to be in outage for wrist-to-base station links. Note that for all links, setting up the balanced and conservative modes is sufficient to guarantee a reliable operation in all cases. In summary to achieve less than 10% outage, the wrist-to-base station and chest-to-wrist link must be used with the balanced or the conservative mode in the outdoor environment, whereas for the other environments all modes can be activated. Meanwhile, the chest-to-base station link can utilize all modes in all the environments.

VIII. CONCLUSION AND FUTURE WORK

In this paper we have investigated transmit power control as a method to enhance the energy efficiency and link reliability simultaneously in BAN applications. We have used experimental channel data to emphasize the necessity of using a power control method in the context of BANs. We then developed 3 practical power control schemes which utilized the channel deviation to recognize changes in channel states. The algorithms were specifically tailored for BAN applications being designed to be flexible, light and easy to implement. The results obtained have shown that the dynamic algorithm is capable of saving up to 35% energy compared to other competing schemes. Meanwhile, the sample-and-hold algorithm allows the transmitter node to less frequently update the transmit power in exchange for between 1 to 10% outage which satisfies the IEEE 802.15.6 standard. Moreover, we also demonstrated some recommended parameters settings, which allow different trade-offs between energy savings and signal reliability to be achieved. The results show that the proposed schemes are suitable for both on-body and off-body BAN communications in typical environments.

In this study, we have clearly demonstrated the effectiveness of the new power control schemes for use in BAN applications. Nonetheless, there are a number of natural extensions of the work which will further prove the utility of the proposed schemes. For example extension to the multiple BAN case where several users (or equivalently BAN nodes) are served by the same base station, which may or may not be body worn. While this study focussed on developing algorithms which are robust in the most common everyday usage scenarios, it is also recommended that further human activities are considered and extended trials are performed over days and possibly weeks of use. Finally, it is worth reiterating that due to the simplicity of their implementation, it is anticipated that the proposed schemes will find application well beyond the area of BANs. In particular, they will be useful for other resource constrained, wireless sensor based applications which are subject to time varying channel conditions.

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⁴The same principle applies to both Algorithm 1 and 2; however for brevity we focus our discussion on Algorithm 3.

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