Analysing the Impact of Mutual Interference in Body Area Networks

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Abstract

The development of electronics and short-range communications gave rise to smart healthcare systems known as body area networks (BAN), to record the vital signs of patients for diagnosis. However, these systems may be located in dense areas, where several networks operate next to each other. Hence, interference occurs, which can adversely affect their proper functioning. Before proceeding with interference reduction or avoidance techniques, it is very important to first analyze this problem under different contexts and scenarios, to better understand it. The aim of this paper is to study the impact of inter-ban interference in body area networks on overall energy consumption, under two different contexts: when the inter-ban distance is varying, and when the amount of nodes in surrounding BANs increases. For this purpose, the two following scenarios are considered: In the first scenario, the distance between two adjacent BANs is decreasing from 6 to 2 m, and the overall energy consumption of the BAN of interest is evaluated. On the other hand, the second scenario highlights the impact of the amount of nodes in an interfering BAN on the overall energy consumption. Simulations were conducted using Castalia 3.3 software. The obtained results showed that when two BANs are located next to each other, if the distance between them becomes smaller, or the amount of nodes in the interfering BAN exceeds that of the reference one, the energy consumption of the BAN of interest will increase, due to the highly experienced interference levels, especially at high data rates.

Keywords Mutual interference · Body area networks · Energy consumption · On-body applications · IEEE 802.15.6

Introduction

A Wireless Body Area Network, commonly known as “WBAN”, is a combination of multiple sensors fixed on the surface or implanted inside the human body [1, 2], to collect various physiological parameters, such as body temperature, glucose levels, heart and respiratory rates [3, 4], or even the calories burnt after a physical activity. These networks are considered as a special case of Wireless Sensor Networks (WSN), although the technical requirements and design challenges of the two mentioned networks are different [5]. WBANs are being used in several applications [6, 7]. In healthcare, they are used for telemedicine and remote patient monitoring [8], which involves supervising daily life activities of patients suffering from specific diseases, either at home or

in hospitals when they need intensive care. WBANs are also used for rehabilitation purposes [9], i.e. to readapt or correct any adverse motion to achieve a target goal (e.g. an ideal position). For example, to help a person who has sustained a brain injury to regain as much autonomy as possible [10, 11]. The applications of BANs are therefore diverse which makes the quality of service requirements differ from one application to another.

WBAN solutions face many challenges during their implementation, and energy efficiency is a major one. With small batteries powering the sensor nodes, network lifetime is a critical consideration. Moreover, this challenge is highly related to the position of nodes, i.e. on-body nodes are easy to replace but implant ones are not. The sources of energy wastage in WBANs are diverse, they are discussed in [12], and include collisions, idle listening, traffic fluctuations, resource allocation techniques, etc. Interference is also a main cause of the depletion of energy sources in WBANs and can adversely affect other important performance indicators. The IEEE 802.15.6 standard [13], created to cover most WBAN applications, offers a wide choice of frequency bands. One of these is the 2.4 GHz narrow band, which is often most preferred [14] as it is unlicensed and its physical layer components are

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available as they are already used in Wi-Fi and Bluetooth [15–17]. Nevertheless, the 2.4 GHz band faces the problem of interference, as several technologies operate within it.

In fact, interference occurs when a BAN hub can hear the signal of another sensor node from an adjacent BAN, this phenomenon is known as mutual interference as shown in Fig. 1, or it may be a signal of another technology operating in the same frequency band, typically the 2.4 GHz ISM band. Such technologies can be Bluetooth (IEEE 802.15.1), Zigbee (IEEE 802.15.4) or WIFI (IEEE 802.11), as shown in Fig. 2, this particular type is known as cross interference. For mutual interference, the IEEE 802.15.6 standard requires the system to operate correctly within a transmission range of 3 m when ten different BANs are located in a space of 3 m³. Nevertheless, when many sensors of different BANs are in close proximity to each other and use the same channel simultaneously, inter-channel interference can still occur, and therefore transmitted packets will collide as shown in Fig. 1.

In mutual interference, neighbouring BANs may use the same channel to transmit their packets, leading to an overlap of the active transmission periods [18] which may impact their performance. In literature, studies that discussed the issue of interference (mutual or cross interference) can be classified into two main categories: interference analysis studies and interference reduction or cancellation studies. This paper is

mainly devoted to the analysis of mutual interference in BANs.

The impact of mutual interference on the performance of BANs has been discussed in several studies [19]. In [20] for example, the authors evaluated the impact of the number of neighbouring BANs on their performance in the case of interference. It was found that when the number of adjacent BANs increases as well as the transmission rate, the packet delivery ratio (PDR) is adversely affected. The impact of inter-BAN distance has also been addressed in various works [21]. X. Wang and L. Cai [22] quantified the minimum network distance that guarantees a signal to interference ratio (SINR) for the boundary nodes and the average SINR of the whole system. It was shown that the minimum network distance should be greater than 7 to 12.5 m to guarantee the SINR for the boundary nodes and at least 9 to 18 m to guarantee the average SINR required by the WBAN. Concerning the MAC layer, a mathematical comparison of three classical multiple channel access protocols in terms of SINR, BER and collision probability was carried out in [23]. These are CDMA, FDMA and TDMA. According to the obtained results, the TDMA protocol was found to be the best in terms of BER and SINR, which makes it suitable for reducing co-channel interference. FDMA is also able to reduce interference in uncoordinated WBANs. However, among the three mentioned protocols, CDMA is the

Fig. 1 Mutual interference in BANs

Fig. 2 Cross interference in BANs

less performant. At the physical layer level, the impact of modulation on interference was also discussed in [24]. A comparison between Differential Binary Phase Shift Keying (DBPSK) and Differential Quadrature Phase Shift Keying (DQPSK) was done in terms of PLR in the case of mutual interference. The previously mentioned authors considered two adjacent BANs and investigated the three following scenarios: 1) the distance between adjacent BANs changes. 2) the number of nodes in the disruptive BAN varies. 3) the packet payload of the interfering BAN also changes. The study showed that as the interference level becomes more important (when the distance between adjacent BANs is small, or the number of nodes or traffic payload in the interfering BAN increase) DBPSK modulation appears to be more resistant to this problem and guarantees a minimum PLR compared to DQPSK. The impact of transmit power levels in the case of mutual interference in BANs was also discussed in [6, 7]. The authors considered both the line-of-sight propagation, modeled by CM3A channel model [25] and temporal variation phenomena. The purpose of the mentioned work is to vary the transmission power of an interfering BAN to see how it affects the BAN of interest in terms of PLR. For this reason, different power levels were considered, and it was shown that PLR is adversely affected when neighbouring BANs transmit their data at a higher power level.

To complete our research work on mutual interference in BANs, we thought it would be useful to discuss the impact of this issue on energy efficiency of BANs, as it is an important challenge to be addressed. The present paper is part of the analysis of the impact of mutual interference in BANs on energy consumption. It studies the effect of two important metrics in every interference scenario, which are: the inter-BAN distance and the amount of nodes per BAN. For this purpose, two BAN prototypes are taken into account, one used as a reference BAN (Ref-BAN) and the other acts as a

disruptive BAN (Dis-BAN). The two models are located near to each other, and the overall energy consumption for Ref-BAN is evaluated according to the following scenarios: 1) the distance separating the two BANs varies from 6 to 3 m. 2) the number of nodes in the disruptive BAN is changing until it exceeds that of the BAN of reference.

The remainder of this paper is organized as follows: section 2 describes the scenarios used in this study. Section 3 highlights the configuration of the studied BAN prototypes, including the adopted channel model, physical and MAC layer settings. The obtained results are presented and discussed in section 4, and section 5 concludes the paper.

Description of the Studied Scenarios

The present study is intended to highlight the impact of mutual interference on the overall energy consumption in BANs. For this purpose, two BANs are set up next to each other. The first one is the BAN of interest, and the second will act as a disruptive BAN, they are named as Ref-BAN and Dis-BAN respectively for the rest of this paper. Therefore, two scenarios of study are adopted: the first one evaluates the effect of the variation of inter-BAN distance on overall energy consumption of Ref-BAN. And the second one highlights the impact of the amount of sensor nodes in Dis-BAN on overall energy consumption of Ref-BAN.

Scenario 1: Changing the Inter-BAN Distance between Ref-BAN and Dis-BAN

To evaluate the effect of the inter-BAN distance on the overall energy consumption, a basic reference BAN model designed for on-body medical applications is used, as described in Fig. 3a. It is composed of ten sensor nodes that transmit

Fig. 3 The case studies of scenario 1: **a** Ref-BAN operates alone. **b** the inter-BAN distance is 6 m. **c** the inter-BAN distance is 2 m

different physiological signs to a coordinator located slightly below the patient's navel. The reasons of the choice of these node positions are given in [24, 26]. The on-body medical applications taken into account in this model are classified as follows:

- *Low data rate on-body medical applications*: it includes all medical applications requiring a data rate of less than 10 kbps, such as body temperature, blood pressure or glucose measurement applications.
- *Medium data rate on-body medical applications*: which covers all medical applications with data rates up to 44 kbps, such as pulse oximetry and Electroencephalogram (EEG) measurements.
- *High data rate on-body medical applications*: it includes all on-body medical applications with data rates up to 72 kbps. Such as the measurement of electrocardiogram (ECG) signals.

The technical requirements for each one of these applications are thoroughly described in one of our latest research papers [26].

To study the impact of inter-BAN distance under mutual interference conditions on the overall energy consumption of Ref-BAN, the three following situations are considered, as shown in Fig. 3:

- Ref-BAN operates alone without being exposed to interference from any adjacent BAN.
- Dis-BAN is functioning at a distance of 6 m from Ref-BAN, as shown in Fig. 3b.
- Dis-BAN is present at a distance of 2 m from Ref-BAN, as shown in Fig. 3c.

Scenario 2: Changing the Amount of Dis-BAN Nodes

The second scenario is aimed specifically at evaluating how the amount of nodes in a neighbouring BAN (Dis-BAN) may impact the energy consumption of the BAN of reference. The number of Ref-BAN nodes in this scenario is always maintained to eleven, while the number of sensor nodes in Dis-BAN is varying. For this purpose, the following case studies are considered:

- **Case 1:** The number of Dis-BAN nodes is lower than that of Ref-BAN. Two situations are considered here:
 - The number of Dis-BAN nodes is 2.
 - The Number of Dis-BAN nodes is 5.
- **Case 2:** The number of Dis-BAN nodes is equal to that of Ref-BAN (eleven nodes).
- **Case 3:** The number of Dis-BAN nodes is higher than that of Ref-BAN, in this case the following two situations are studied:
 - The number of Dis-BAN nodes is 15.
 - The number of Dis-BAN nodes is 21.

Configuration of the Studied BAN Models

For the two BAN models of this study, the path loss model is identical, as well as the MAC and PHY layer configurations, the only difference being in the second scenario where the number of nodes of the disruptive BAN is variable.

The Adopted Energy Consumption Model

The adopted energy consumption model presents the total energy consumed in a network Econ by Eq. 1:

$$E_{con} = E_{TX} + E_{RX} \quad (1)$$

Where E_{TX} is the energy consumed by the transmitting nodes and E_{RX} is the energy consumed by the receiver (hub).

For a successful packet transmission, the consumed energy E_S is given by Eq. 2:

$$E_S = E_{TX} + E_{SB} + E_{SC} \quad (2)$$

Where:

- E_{SB} : is the consumed energy during the back-off time for a successful packet transmission.
- E_{SC} : is the consumed energy during collisions for a successful transmission.

E_{TX} is given by Eq. 3:

$$E_{TX} = E_{TX,D} + E_{RX,A} \quad (3)$$

D and A refer to data packets and ACK, respectively.

The consumed energy during a data packet transmission is given by Eq. 4, where T_{TX} and P_{TX} stand for the transmission time and power of a data packet respectively.

$$E_{TX,D} = T_{TX} \cdot P_{TX} \quad (4)$$

The consumed energy when receiving an ACK is given by Eq. 5, where T_{ACK} and P_{RX} are the time and reception power of an ACK respectively.

$$E_{RX,A} = T_{ACK} \cdot P_{RX} \quad (5)$$

E_{SB} and E_{SC} are given by Eqs. 6 and 7:

$$E_{SB} = T_{SB} \cdot P_{IDLE} \quad (6)$$

Where T_{SB} is the back-off time, and P_{IDLE} is the power used in idle mode.

$$E_{SC} = N_C \cdot (P_{TX} \cdot T_{TX} + T_C + P_{TX} \cdot T_{TX}) \quad (7)$$

Where N_C is the number of collisions for a successfully transmitted packet, and T_C is the collision time.

For unsuccessful packet transmission, the consumed power when a packet is deleted E_{DP} is given by Eq. 8:

$$E_{DP} = E_{DPB} + E_{DPC} \quad (8)$$

Where:

- E_{DPB} is the consumed energy during the back-off time for a deleted packet.
- E_{DPC} is the consumed energy due to collisions for a deleted packet.

E_{DPB} and E_{DPC} are given by Eqs. 9 and 10 respectively:

$$E_{DPB} = P_{IDLE} \cdot T_{DPB} \quad (9)$$

$$E_{DPC} = (r + 1) \cdot (P_{TX} \cdot T_{TX} + T_C + P_{TX} \cdot T_{TX}) \quad (10)$$

Where r is the number of retransmissions of a packet.

Physical Layer Settings

Channel Model

The two studied BAN models operate in the 2.4 GHz narrow band, more specifically at 2.45GHz. Furthermore, the signal propagation between nodes takes place on the body surface, with consideration to non-line of sight conditions, since it is possible to have obstacles between two communicating nodes in a BAN. The channel model adopted for this study is called CM3B[27], in which the path loss in a BAN decreases exponentially around the body perimeter, and flattens out at long distances. CM3B is also incorporated in the IEEE802.15.6 standard. A detailed description of the components of this model is presented in our previous works [24, 28].

Transmission Data Rate

The proposed reference BAN model is dedicated to non-invasive on-body medical applications. As previously mentioned, these are classified as low, medium and high data rate on-body applications.

Therefore, the simulations of the overall energy consumption of Ref-BAN, in the scenarios presented previously, will be conducted for the following three transmission data rates: 10 kbps, 40 kbps and 72 kbps representing the targeted medical applications.

Radio Parameters

The adopted radio module has been proposed first by A. Wong et al. [29], it is particularly designed for BAN nodes operating at 2.4GHz or 900 MHz. At 2.4GHz, this radio can be used for two technologies: IEEE 802.15.6 and Bluetooth Low Energy (BLE). For the IEEE 802.15.6 standard (the adopted technology by the two BAN prototypes of this study),

the proposed radio offers two differential modulation schemes: DBPSK (Differential Binary Phase Shift Keying) and DQPSK (Differential Quadrature Phase Shift Keying). The radio also provides three transmission power levels: -10 dBm, -3 dBm and 0 dBm. According to the recommendations of the IEEE 802.15.6 standard, nodes in a BAN must be able to transmit their packets with a minimum power of -10 dBm, and never exceed 0 dBm [30].

Therefore, the transmission power adopted in the two BAN models of this study is -10 dBm. Moreover, DBPSK modulation is used for low transmission data rates while DQPSK is reserved for high data rate packet transmissions. More details on the physical layer configuration used in both Ref-BAN and Dis-BAN is presented in Table 1.

MAC Layer Settings

The MAC layer setup used in this work is hybrid, it combines two channel access modes: a random access mode based on CSMA/CA and a scheduled access mode based on TDMA. An exhaustive description of the adopted MAC layer configuration is given in one of our previous works [24]. More parameters related to the MAC layer are also listed in Table 1.

Simulation Results and Discussions

Simulation results of the two scenarios of study are presented and discussed in this section.

Scenario 1: The Impact of Inter-BAN Distance on the Overall Energy Consumption of Ref-BAN

Figure 4 depicts the overall energy consumption of Ref-BAN nodes in the three cases of coexistence (in the absence of interference, and when Dis-BAN is located at different distances from Ref-BAN). The distances that yielded significant results are 6 m and 2 m. As mentioned earlier, the study of the effect of inter-BAN distance on energy consumption is carried out for three transmission data rates: 10 kbps, 40 kbps and 72 kbps.

When Ref-BAN is not experiencing interference (absence of Dis-BAN) the overall energy consumption is around 7 joules, with a slight difference noted when the transmission data rate increases (7.35 J for 10 kbps, 7.55 J for 40 kbps and 7.6 J for 72 kbps). However, as soon as the disturbing BAN is nearby, the consumed energy rises to reach 12 joules at a distance of 6 m (11.99 J for 10 kbps, 12.57 J for 40 kbps and 12.66 for 72 kbps) with a light increase when the distance is reduced to 2 m (12.57 J for 10 kbps, 12.67 J for 40 kbps and 12.78 J for 72 kbps). To better explain these results, a detailed simulation of what happens on the mac layer when Ref-BAN is experiencing.

interference is shown in Fig. 5. As can be noticed, Fig. 5 presents packet breakdown at the MAC layer of Ref-BAN in the absence and presence of mutual interference at 72 kbps. A buffer overflow in the receiving hub is noticed in the case of interference, this is caused by the collection of packets from the adjacent Dis-BAN in addition to Ref-BAN packets, especially when the distance between the two networks is small. As a result,

Table 1 Simulation parameters

Simulation parameters	Low Rate: 10 kbps	Medium Rate: 40 kbps	High Rate: 72 kbps
Modulation scheme	DBPSK	DQPSK	DQPSK
Transmit Power (dBm)	-10	-10	-10
Receiver Sensitivity (dBm)	-104	-96.5	-96.5
Clear Channel Assessment (CCA) Threshold (dBm)	-95	-95	-95
Payload (Bytes)	100	100	100
Simulation time (s)	151	151	151
Frequency of operation (Ghz)	2.45	2.45	2.45
Channel Model	CM3B	CM3B	CM3B
Beacon period in Time slots (TS)	32	32	32
Random Access Period (TS)	2	2	2
Scheduled Access Period (TS)	3	3	3
Time slot Duration (s)	10	10	10
Consumed Energy in the Transmission Mode (mW)	5.9	5.9	5.9
Nodes initial Energy (Joules)	$18,720$	$18,720$	$18,720$
Sigma CPU clock drift	0.00003	0.00003	0.00003
Buffer size (Bytes)	48	48	48

Fig. 4 The impact of inter-BAN distance on the energy consumption at low, medium and high data rates

buffer overflow, manifesting as large packet queues, is potentially the main factor causing high energy consumption. This saturation can also affect other BAN performance metrics such as throughput.

Fig. 5 Data packet breakdown at the MAC layer in absence and in case of mutual interference at 72 kbps

The problem of buffer overflow, experienced in the case of mutual interference, is also related to the increased transmission data rate of both BANs. Therefore, Fig. 6 shows the percentage of packets failed due to buffer overflow for the three studied

Fig. 6 The Impact of increased transmission data rate on buffer overflow in the case of mutual interference (the distance between the two BANs is 6 m)

data rates, in the case of mutual interference, when the distance between Dis-BAN and Ref-BAN is 6 m. It is noted that the percentage of non-received packets due to buffer overflow increases with high transmission data rate, thereby causing more lost packets. i.e. At 10 kbps, 49.59% of packets are lost due to the problem of buffer overflow. However, when the data rate increases to 72 kbps, for example, this percentage also increases

to reach 66.19%. To fix this problem, a buffer size reduction can help to reduce the overall energy consumption of Ref-BAN. However, it may impact other performance factors such as throughput. This is shown in Figs. 7 and 8.

Figure 7 shows the overall energy consumption of Ref-BAN for different buffer sizes. The transmission data rate is fixed to 40 kbps, and the distance between the two BANs is

Fig. 7 The overall power consumption of Ref-BAN for different buffer sizes at 40 kbps

Fig. 8 Throughput for different buffer sizes at 40 kbps

6 m. Several buffer sizes have been analysed, but only the most significant ones are shown in Fig. 7. According to the obtained results, it is noticed that the overall energy consumption of Ref-BAN in the case of mutual interference can be optimized by reducing the size of the node buffer (the overall energy consumption of Ref-BAN is 12.46 J when the buffer

size is 8 bytes, and 12.68 J when the buffer size is 88 bytes). However, such improvement in energy consumption does not come without affecting the throughput.

Figure 8 shows the impact of reducing the buffer size of nodes on throughput. Using a reduced buffer size may cause data packet losses, manifested by minimal throughput values.

Fig. 9 the energy consumption of Ref-BAN in function of the number of Dis-BAN nodes at 10 kbps

Fig. 10 The energy consumption of Ref-BAN as a function of the number of Dis-BAN nodes at 40 kbps

When this size is 8 bytes for example, a much smaller number of packets are received than when the memory size is relatively

larger (19,734 packets/s when the buffer size is 8 bytes and 27,306 packets/s when the size is increased to 48 bytes).

Fig. 11 The energy consumption of Ref-BAN in function of the number of Dis-BAN nodes at 72 kbps

Scenario 2: The Effect of the Number of Dis-BAN Nodes on Energy Consumption

Figures 9, 10 and 11 represent the overall energy consumption of Ref-BAN for the three discussed cases where the number of Dis-BAN nodes is varying, at 10 kbps, 40 kbps and 72 kbps respectively. The modulation scheme adopted in these three simulations is DQPSK.

Based on the results of Figs. 9, 10 and 11, it can be seen that when the number of Dis-BAN nodes is lower than that of the Ref-BAN, the energy consumption of Ref-BAN is minimal. This is due to the minimal level of interference that Ref-BAN experiences in this case. In a previous study [24] we have already shown that the variation of the number of nodes in the disruptive BAN has a direct impact on the level of interference experienced, and consequently on throughput. When the number of Dis-BAN nodes exceeds that of the Ref-BAN, the overall energy consumption also increases for the three studied transmission data rates. This shows that the higher the number of nodes in the disruptive BAN, the higher the level of experienced interference. This can also cause high packet loss rates. Furthermore, at the MAC layer, as with the first scenario, the impact of mutual interference results in a saturation of the nodes' buffer. Therefore, reducing the buffer size can help to lower the energy consumption, but can have a negative effect on throughput.

The deficiency of energy sources in BANs can also be improved by integrating energy harvesting solutions, that transform body scale clean energies into electrical energy [31, 32], to supply node batteries.

Conclusion

In this paper, an analysis of the impact of mutual interference on energy consumption of a BAN was performed. The study covered two scenarios: in the former the impact of the inter-BAN distance on energy consumption was presented. While in the latter, the effect of the amount of nodes in Dis-BAN on Ref-BAN energy consumption was discussed. The conclusions that can be drawn from the studied scenarios is that the fact of decreasing the distance between adjacent BANs can increase the consumed energy of BAN nodes. This is due to the fact that when the level of interference increases (small inter-BAN distance), BANs placed next to each other are able to hear signals from one another, which leads to nodes buffer overflow. These same results are also found when the amount of nodes in the adjacent (disturbing) BAN exceeds that of the reference one, causing large packet queues, that are often due to collecting packets from other adjacent BANs. To remedy this problem, reducing the buffer size can help to decrease the consumed energy, but at the expense of some equally important metrics such as throughput.

The issue of energy efficiency in BANs in the case of interference is a real challenge that needs to be taken into account before the conception of any BAN solution. For this reason, a study of energy harvesting techniques that are suitable for our BAN model will be carried out in a future work.

Availability of Data and Material The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code Availability Not applicable.

Authors' Contributions This paper studies the effect of mutual interference in BANs on total energy consumption in two scenarios where both the inter-ban distance and the amount of nodes per BAN are varying.

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Declarations

Ethics Approval Not applicable.

Consent to Participate The authors are consent of this paper submission.

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