Interference Mitigation and Coexistence Strategies in IEEE 802.15.6 Based Wearable Body-to-Body Networks

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Abstract. This paper is focused on understanding the impact of interference in wearable wireless body-to-body networks (BBN). We have presented and compared two *non-collaborative* schemes (i.e., Time-shared and channel hopping) and one *collaborative* technique (i.e., CSMA/CA). For the performance evaluation, different metrics such as packet error rate (PER), packet reception ratio (PRR), energy consumption and latency are considered. In order to have accurate evaluation, a comprehensive and realistic simulation framework and cross-layered based system models are developed in a network simulator. Finally, the results show that, for *non-collaborative* channel hopping approach outperforms the time shared scheme in all the metrics especially even at lowest transmission power. Whereas, CSMA/CA approach performs much better in terms of delay as well as PRR, however, it is costly in terms of energy consumption.

Keywords: Wearable body-to-body networks · Interference mitigation · Coexistence · IEEE 802.15.6 · Performance evaluation

1 Introduction

A Wearable Wireless Sensor Networks is a self-organized network at the human body scale. It consists of heterogeneous smart devices which are low-power, miniaturized, hardware-constrained (with limited processing and storage capabilities), and attached to (or implanted inside) a human body. These devices can be sensors (to sense, transmit and receive data), actuators (to react according to the perceived data) or coordinators (to act as a gateway for the external network). Typically sensors are connected to monitor physiological signs (e.g. heartbeat, temperature, etc.), movement and activity (e.g. acceleration, orientation etc.) and surrounding environments (e.g. temperature, toxic gases, etc.). Wearable wireless sensor networks have gained significant attention in daily life applications. In health-care sector, remote and mobile monitoring of patients from physician or hospitals is a reality, self monitoring and early diagnosis is also possible. Athletes and players uses various wearable devices to maintain

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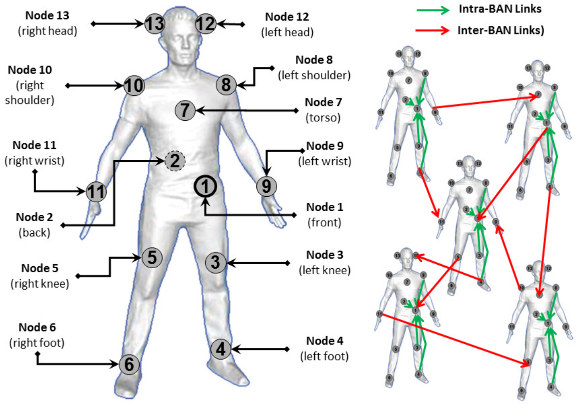

Fig. 1. Intra-BAN and Inter-BAN Networks and Interference Scenarios.

their fitness. Further the concept of augmented reality is getting mature due to convergence of technologies, data and computing.

In this work, we will emphasize on our on-going research with an application scenario of wearable wireless sensor networks for rescue and critical operations for emergency and disaster management [1]-[2]. In the given application context, most often, the existing infrastructure is either damaged or over-saturated, therefore, body area networks will create a new network for wireless communication. Further, multiple human bodies will enable coordination and communication through wireless Body-to-Body Networks (BBN). Figure 1, shows an example in which number of nodes are placed on a body for the intra-body communication and multiple bodies are closely located to effectively coordinate and communicate with each other in rescue and disaster operation. The coordinating nodes are responsible and controlling the communication on the body as well as between the bodies. However, one of the fundamental problem while being close to each other is that the sensors connected on one body interfere with the sensors connected on the other bodies and therefore, can interrupt and interfere the intra and inter body communications. In this regard, most of the literature focus on adjacent channel interference (i.e., interference from other standards), whereas interference mitigation and coexistence schemes for BBN is very limited. The focus in this paper is to ensure effective communication within and between multiple bodies by applying suitable coexistence strategies. In this context, recently released IEEE 802.15.6 standard proposed three methods including *beacon shifting*, *channel hopping* and *active superframe interleaving*. The performance of these strategies are yet to be evaluated especially in the context of BBN. Concerning that, we have considered a simulation-based approach mainly because of lack of commercially available IEEE 802.15.6 compliant radio transceiver for prototyping and experimentation. Further, BBN is very complex networks to analyze analytically because there are many parameters with huge set of possible combinations.

The contributions of this paper are as follows. First, we proposed modified, simpler and more efficient versions of coexistence schemes. For non-collaborative approach, *time shared* mechanism is implemented which is a simplified version of *beacon shifting* since it does not has to maintain big table with beacon shifting indexes. For the case of *channel hopping* technique a random channel selection method is adapted. Further, a modified and simpler IEEE 802.15.6 compliant *carrier sense multiple access/collision avoidance CSMA/CA* based *collaborative* coexistence strategy is implemented and evaluated. Second, as the reliability and quality-of-service are key performance constraints for the given applications, therefore, the performance of the coexistence strategies are evaluated in terms of packet error rate, packet delivery ratio, packet latency and energy consumption. The evaluation is achieved under realistic environment including accurate intra and inter BAN mobility and radio link modeling, realistic pathloss and channel models, IEEE 802.15.6 proposed MAC models (i.e., CSMA/CA and scheduled access), which are developed for BBN systems.

2 Related Works

Generally the interference mitigation is classified into *collaborative* and $non-collaborative$ coexistence techniques. In collaborative methods multiple nodes interact with each other to manage coexistence, whereas, in non-collaborative multiple nodes manage coexistence without any interaction. The initial research studies on WBAN interference mainly concentrate on the impact from other technologies (aka., adjacent channel interference) such as IEEE 802.11, IEEE 802.15.1, *etc.* It is clear from the previous research works such as [3–6], that there is a dominant interference from other networks in WBAN. These approaches of interference analysis are only enough for intra-BAN communication, where each node is synchronized with its coordinator and are configured at the same transmit power. However, with an advent of body-to-body communications, inter-BAN interference and its mitigation is a new problem. Merely a few studies targeted this issue, for example, [7] focused the study on the measurement of the coupling between 10 bodies in a room at (2400-to-2500) MHz. An average pathloss of -67.9 dB and standard deviation of 5 dB was observed. These bodies were separated by 1-to-5 meters in hospital environment. Though the measurements conducted are interesting, however it is only limited to static case without any mobility considerations. Further, it does not show how much application performance loss is expected with evaluated interference. Finally, the coexistence strategy results are limited to only packet delivery. Three co-located WBANs were configured to operate at different transmission power levels, with chirp and duty cycling sampling receivers in [8]. The results showed that under high traffic density the chirp receiver is more immune to interference than the sampling receiver where the PLR was around 1% for up to 10 co-located users. However, the transceivers operate at *ultra wide band* (UWB), whereas the impact of interference in *narrow band* is much more stronger and evident.

More recently, the authors addressed in [9] the issue of co-channel interference between co-located multiple BANs. Two uncoordinated approaches are presented, first, a semi-random strategy is used to re-allocate the slots in TDMA mode. A coordinating node checks if the total interference experienced by all the receiver nodes (based on the random slot assignment) is less then the current slot, the slot assignment for the next frame changes otherwise, it remains unchanged. In the second approach, a minimum interference slot assignment algorithm is chosen instead of assigning random slot. These proposed approaches are limited due to number of un-realistic assumptions. First in random slot assignment, the performance of actual throughput and delay suffers especially due to lack of realistic mobility, low-to-high traffic and nodes density. Further, the actual interference is not calculated or estimated instead it is based on assumptions. Finally no coexistence method of IEEE 802.15.6 standard is evaluated. With reference to inter-BAN interference mitigation, the recently released IEEE 802.15.6 standard (targeted for WBAN), has proposed several methods for coexistence. These include, *beacon shifting*, *channel hopping* and *active superframe interleaving* [10]. To best of our knowledge, the performance of these methods in particular with inter-BANs context is yet to be evaluated. Further, all these methods are non-collaborative and are based on pre-defined strategies. In addition to that, in this paper we will also analyze the impact of collaborative technique using IEEE 802.15.6 compliant CSMA/CA method. This can be considered as implicit collaborative technique in which nodes do not share any specific information to each other but the interference can be minimized through only proper channel sensing.

3 System Models

Wireless Body-to-Body Networks (BBN) is relatively a new dimension of WBAN in which multiple bodies interact and share certain information. Fig. 1, shows an overview of on-body links and body-to-body links. In this section, we will explain various cross-layer components of the BBN system.

3.1 IEEE 802.15.6 MAC Models

The IEEE 802.15.6 standard provides a great flexibility to the researchers and developers to adapt the medium access as their requirements. In classical healthcare WBAN systems, *time division multiple access* (TDMA) based medium access control is most often considered. Every sensor node has a dedicated slot to transfer its data to the other sensors or coordinator. Moreover, works such as [11]-[12] can further help to optimize the slot scheduling based on the traffic load. Historically, limited attention has been given to CSMA/CA, however, very-low duty cycle CSMA/CA based protocols such as [13] seems very attractive. IEEE 802.15.6 MAC can be implemented through CSMA/CA, TDMA, slotted aloha, scheduled access as well as polling and posting mechanisms. The MAC layer can operate in three different modes. In beacon mode with superframe boundary,

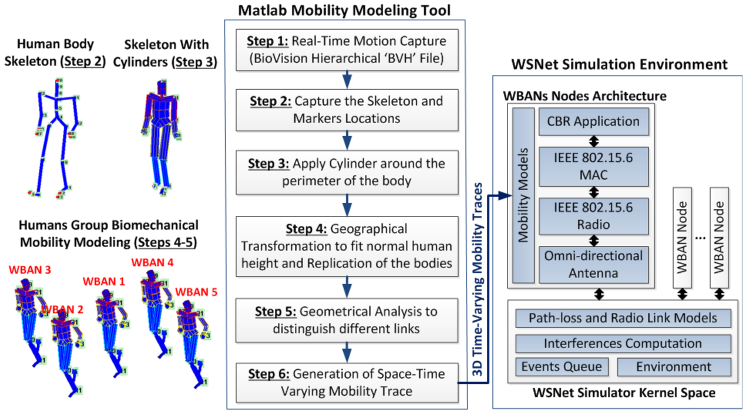

Fig. 2. Joint Biomechanical, Group Mobility and Radio Link Modeling for BANs and BBNs.

the higher priority and emergency data transfer can execute in exclusive access phase (EAP) including both EAP1 and EAP2. For regular non-emergency traffic two random access phase (i.e., RAP1 and RAP2) can be considered. Both EAP and RAP can use only CSMA/CA or slotted aloha channel access schemes. Further, managed access phase (MAP) can be scheduled both in beacon enabled and non-beacon modes. Application-specific optimal MAC configurations are presented for intra-BAN in one of our earlier work [14]. Those configurations are evaluated through physical and MAC parameters for the scheduled access. In this paper, we have extended the work for body-to-body communications through extensive simulations. IEEE 802.15.6 proposed CSMA/CA MAC and scheduled access MAC are implemented in a packet-oriented network simulator as explained later in section 4.1 for an inter-BAN analysis.

3.2 Realistic Mobility and Physical Layers Modeling for BBNs

The accurate mobility, path-loss and radio link modeling is a key requirement in order to get more insight into the performance of wireless communication stacks under real deployment and operating assumptions [15–17]. This is especially true in the context of BANs and BBNs, whose radio channels might undergo harsh multi-path fast fading and time-varying slow fading due to human body shadowing effects [18]. To that end, we consider in this work the Intra-BAN biomechanical mobility and radio link models which we recently introduced in [15], and we extend these to handle the inter-BANs case.

Intra/Inter-BANs Biomechanical Mobility and PathLoss Modeling. Modeling the mobility and posture behaviors of real human bodies is a complex task. One solution consists in exploiting real-time motion capture data and to couple them with geometrical transformation and analysis techniques to properly investigate the performance of BANs and BBNs under different mobility scenarios (*e.g.* walking, running, exercising, *etc*). As shown in Figure 2, our proposed Intra and Inter-BANs mobility modeling is based on six main steps: ***Step 1***: real motion capture measurements are extracted into our Matlab mobility modeling tool [15]; ***Step 2***: the complete human body skeleton is captured which consists in a set of markers (*i.e.* the joints between the different parts of the body) and segments (*i.e.* the body parts). These markers provide the dynamic distances among all the locations over time; ***Step 3***: In order to properly model the human body parts (*e.g.* arms, torso, head, legs, *etc.*), cylinders are applied around the different segments of the human body to take into account body shadowing effects; ***Step 4***: geographical transformations are then applied in order to scale the dimensions into a normal human height and width. Moreover, the determined human body is replicated into a configurable numbers of other human bodies in order to enable the simulation of complex and highly dynamic inter-BANs scenarios; ***Step 5***: geometrical analysis is thus applied in order to determine the types of all the available links (*e.g.* LOS or NLOS, Intra or Inter BANs) and during the whole trace duration. Exact link types during mobility are evaluated by checking the intersection of the cylinders between all the links. If a link intersects with a cylinder, then the link is declared as NLOS, otherwise it is in LOS state; ***Step 6***: finally, space-time varying links and mobility traces are generated and stored in an external file, which ultimately can be fed into the **WSNet** packet-oriented simulation environment [16] to enable the realistic performance evaluation of high level communication protocols. More details about the six steps can be found in [14]. Once the space-time varying links and mobility traces are properly generated for a given mobility scenario, channel models can be applied in order to assess the performance of radio-links. The IEEE 802.15.6 standard has already proposed various channel models, including the *CM3* (*body surface to body surface*) and *CM4* (*body surface to external*) models. However, it was shown that these models provide only basic distance-based path-loss without any time varying effects and correlations features [15]. Due to these limitations, the enhanced IEEE 802.15.6 path-loss models are used as presented in [15] and [19].

Interference Modeling. In order to correctly model the interference which might disturbs the reception of packets at the physical layer, one common way consists in replacing the SNR (*signal-to-noise-ratio*) [15] by a SINR (*signal-to-interference-plus-noise-ratio*). Sources of interference include Intra-BAN and/or Inter-BAN nodes operating in the same frequency band, *i.e., co-channel interference*, or in different frequencies bands, *i.e., adjacent channel interference.* The proper calculation of the SINR value for a given radio link, between the two nodes i (transmitter) and j (receiver), requires the knowledge of all the signals which are currently and concurrently being received at the receiver j. At any time instant t, the current SINR value can be computed as follows:

$$SINR_{ij}^{t}[mW] = \frac{P_i^{TX} \cdot PL(d_{ij})}{N_j + \sum_{k \neq i,j} \alpha_{ik} \cdot P_k^{TX} \cdot PL(d_{kj})}, \tag{1}$$

where P_i^{TX} stands for the transmission power of the transmitter node i; N_j is the power of the thermal background noise at the receiver node j; α_{ik} the rejection factor between the channels associated with the nodes i and k ($\alpha_{ik} = 1$ in this work); P_k^{TX} is the transmission power of the interfering node k. We consider a full interference model where any node k can potentially generate interference at a given receiver j.

Radio Link Modeling. Finally, in order to determine if a given transmission was successful (despite of interference), it is important to evaluate the corresponding *packet-error-rate* (PER), as: $PER_{ij} = 1 - (1 - BER_{ij}^{t})^{n}$; where n is the packet length in bits, and BER_{ij}^{t} is the corresponding *bit-error-rate* which is computed based on the current SINR level at time t (*i.e.* $SINR_{ij}^{t}$), and the considered physical layer characteristics (*e.g.* data rates and modulation schema), as follows:

$$BER_{ij}^{t} = \begin{cases} 0.5 \times e^{-Eb/No} & \text{DBPSK} \\ Q(\sqrt{4 \times Eb/No} \times sin(\pi/4 \times \sqrt{(2)})) & \text{DQPSK} \end{cases} \tag{2}$$

Where, Eb/No is the energy per bit to noise power spectral density ratio in dB which is computed based on the current SINR level, as: $Eb/No[dB] = SINR_{ij}^{t}[dB] + 10 \times log_{10}(BW/R)$; where BW is the bandwidth in Hz, and R is the data rate in bps.

IEEE 802.15.6 Compliant Interference Mitigation and Coexistence Strategies. The IEEE 802.15.6 standard proposed three techniques for coexistence as briefly mentioned earlier in sec. 2. With reference to beacon shifting technique and in general a beacon packet (transmitted by a coordinator) contains number of important information. It includes timings of the superframe including beacon period, nodes slot duration, number of the slots assignments, sleep duration, coexistence methods, etc. The beacon shifting is important and required to avoid the collisions of the beacons between multiple BANs. This is achieved by having a different pseudo random sequence at each BAN coordinator which helps to randomize the start of the superframe. However, this method alone does not guarantee the interference avoidance between multiple BANs. To have more reliable coexistence mechanism, in this paper, we adapted beacon shifting technique as time-shared approach. In this approach, during the active duration of one BAN, all the other BANs will be in sleep mode and the body-to-body interference can be avoided. This technique does not require to manage any random sequence and is more simple to implement especially under static network where each superframe period is selected according to number of BANs in the surroundings. Channel hopping is another coexistence approach proposed in IEEE 802.15.6 standard which can be applied in scheduled MAC.

In this method the coordinator, generate a channel hopping sequence based on 16-bits Galois linear feedback shift register (LFSR) with a generator polynomial function: $g(x) = X^{16} + X^{14} + X^{13} + X^{11} + 1$. More details on the channel separation and exact calculation of channel hop can be found in [10]. In channel hoping technique, we used a random channel mechanism with every channel has equal probability to be selected. Each BAN operate in one fixed channel for its intra-BAN communication. In narrow band spectrum, there are 79 channels which can be used within the frequency range of $[2400 - 2483.5]$MHz, having center frequency as $fc = 2402.00 + 1.00 \times nc(MHz)$, where $nc = 0, 1, ...77, 78$. Finally we have implemented CSMA/CA medium access method, which can be considered as a implicit collaborative technique for coexistence.

4 Performance Evaluation

In order to understand the impact of body-to-body interference, first, a reference scenario is considered in which multiple bodies are located in close vicinity to communicate without any coexistence strategy. Second, three coexistence strategies (as explained in previous section) are implemented and their results are compared and presented in the following sections.

4.1 Simulation Setup

A packet-oriented network simulator called **WSNet** [16], is used as shown in Fig. 2. It contains various models for wireless sensor networks, wireless local area network and adhoc networks. However, previously it does not contain WBAN specific modules. Therefore, we have developed WBAN specific modules which are explained in section 3 with focus on IEEE 802.15.6 standard compliance. An overview of the developed frame work is shown in Fig. 2. Following are the brief details of the development. The simulation setup is based on version 3.0, which is an up-to-date version of **WSNet**. We consider 5 human bodies, each of them having one coordinating node and 11 sensor nodes as shown in Fig. 1. Five co-located BANs are moving altogether within a distance of 3 meters apart (please note that, this is in compliance with the IEEE 802.15.6 standard in which upto 10 BANs can co-locate in volume of $(6 * 6 * 6)m^3$. At the application layer, consistent packets of 50 bytes of payload, are generated using CBR (constant bit rate) model. The packets are generated at a rate of 100 ms (which satisfy most of the medical signals requirements (i.e., upto 4 Kb/s as effective throughput) [14]). From the application layer, every packet is parsed into the MAC layer. CSMA/CA and scheduled access MAC protocols are developed based on the IEEE 802.15.6 standard. At the PHY layer, *differential quadrature phase shift keying* (DQPSK) modulation model is developed for the *narrowband* (2450 MHz), using the formulas of EbNo, BER and PER as shown in Sec. 3.2. Enhanced IEEE 802.15.6 pathloss models (cf. Sec. 3.2) are implemented. Finally, the real-time motion captured-based inter-BAN mobility traces are imported in **WSNet** which provides accurate space and time variations. By using all the above explained models, the WSNet's XML configuration files (i.e., **xml**) are generated as follows: the number of BAN varies from

1 to 5, transmit power varies between 0 dBm, -10 dBm, -20 dBm and -25 dBm. The coexistence schemes varies from the reference scheme (i.e., without any coexistence) to time-shared, channel hopping and CSMA/CA schemes for 50 iterations and with 95% confidence intervals. The simulations are executed for walking, sitting/standing and running mobility patterns for a duration of 63 sec.

4.2 Results

After having accurate simulating environment, in this section, four performance metrics i.e., PER, PRR, Energy Consumption and Packet Latency, are considered for the evaluation of both *collaborative* and $non-collaborative$ schemes under the given application context. At first, average PER distribution is computed as shown in Fig. 3, using accurate radio link model (i.e, explained in Sec. 3.2). It can be noticed that, in a reference scenario (i.e., Fig. 3-a), as the number of BANs increases from 2 to 3, the PER starts increasing sharply and reaches to 1. In comparison, all the co-existence schemes perform much better, only CSMA/CA based approach suffers marginally when number of BAN reaches beyond 3. For the case of PRR, the worse case under lowest transmission power is presented in Fig 4-a. PRR for reference scenarios for 1 BAN is 94.24%, however, as the BAN increases from 2 to 3 the PRR reduces to 0%. It can be seen that, both channel hopping and time-shared perform much better with PRR is above 95% even under -25 dBm. For the case of CSMA/CA, it performs within 95% requirement as long as the transmission power is -20 dBm, for the case of -25 dBm, its performance degrades significantly as can be seen in Fig 4-a. Further, more detailed results of PRR are presented in Tab. 1. Concerning the average packet delay of a single transmission at the lowest transmit power, for the reference scenario as the number of BAN increases from 2, all the packets starts colliding and the coordinator does not receive any packet. For the coexistence schemes, channel hopping and CSMA/CA has a consistent delay, whereas time shared has gradual increase with the increase of BANs as shown in Fig 4-b. More details can be seen in the Tab. 1. Finally for the energy consumption, different current consumption values are considered from TI's cc2420 radio transceiver. For example, for transmission, [17.4 11 9.2 8] mA is used against the power levels (i.e., [0 -10 -20 -25] dBm). For the reception and idle modes, 19.7 mA is used, whereas for the sleep 0.9 mA is used. The energy consumption is estimated by considering a battery of 3 volts. The results are shown in Fig 4-c and Tab. 1. It can be observed that, for the reference scenario, the energy consumption increases nearly 10 times as the number of BANs increases upto 2 and then it matches with CSMA/CA which consumes maximum energy as the nodes are always in active state. Channel hoping and time-shared schemes perform more energy efficient even under higher number of BANs. To conclude, there is a trade-off between *collaborative* and $non-collaborative$ coexistence techniques. CSMA/CA performs well for PER/PRR until -20 dBm, however, the performance degrades significantly at -25 dBm, whereas, both time-shared and channel hopping schemes performs much better. The main advantage of collaborative approach is that it has minimum delay which could be important

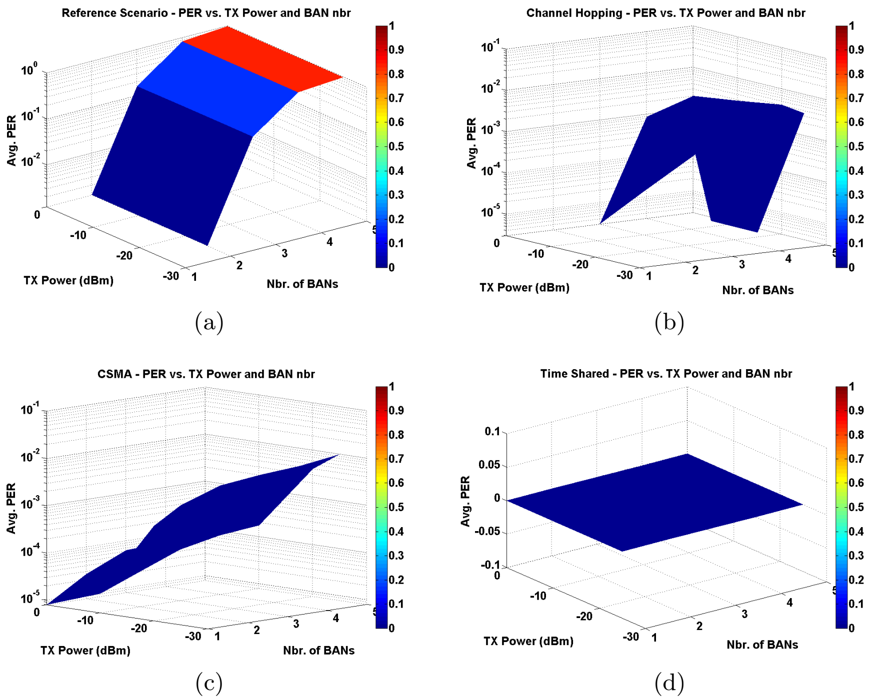

Fig. 3. Packet Error Ratio Distribution of Coexistence Schemes, (a): Reference Scenario, (b): Channel Hopping, (c): CSMA/CA and (d): Time shared

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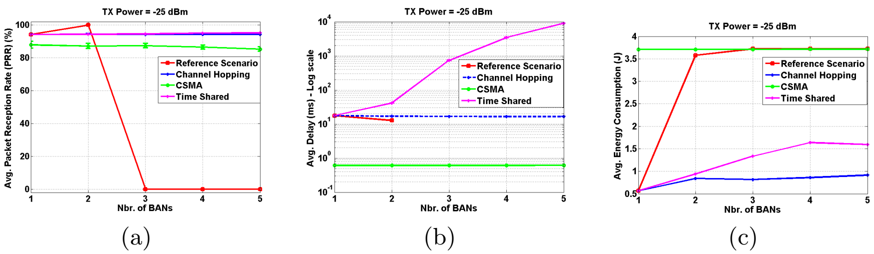

Fig. 4. (a): Average packet reception ratio for multiple BANs in various coexistence schemes. (b): Average packet delay for multiple BANs under coexistence schemes. (c): Average energy consumption for multiple BANs in different coexistence schemes.

for time critical applications. however, it has much higher energy consumption as the nodes are active all the time which could be optimized in the future by applying low power listening protocols. Finally, channel hopping is appeared as the best scheme for $non-collaborative$ approach, in which all the performance metrics are optimized under lower transmission power.

Table 1. PRR, energy consumption and latency under varying TX power and BANs for coexistence schemes.

Performance Metrics	TX Power (dBm)	BAN (nbr)	Reference Scenario	Channel Hopping	CSMA/CA	Time Shared
PRR (%)	-20	1	99.78	99.76	97.20	99.77
		3	0	99.77	94.55	99.76
		5	0	99.77	93.84	99.76
	0	1	100	100	99.76	100
		3	0	100	99.01	99.99
		5	0	100	98.65	100
Latency (ms.)	-20	1	12.7	12.7	0.52	12.5
		3	Inf.	12.6	0.54	39.2
		5	Inf.	12.6	0.54	6460
	0	1	12.5	12.7	0.51	12.5
		3	Inf.	12.4	0.52	38.5
		5	Inf.	12.5	0.52	6349
Energy(J)	-20	1	0.55	0.54	3.71	0.54
		3	3.72	0.84	3.71	1.31
		5	3.72	0.92	3.71	1.63
	0	1	0.55	0.55	3.72	0.55
		3	3.72	0.84	3.72	1.31
		5	3.72	0.82	3.72	1.63

5 Conclusion

In this paper we have analyzed the impact of interference in wearable wireless body-to-body networks. First of all, rescue and critical application based scenario is considered and corresponding system models are developed. The models are developed around IEEE 802.15.6 standard in a network simulator called WSNet. The standard's proposed channel models for narrow band are enhanced to have space and time variations as well as dynamic distances among all the nodes on the body. Accurate radio-link and mobility models are developed for both, on-body (i.e., by using bio mechanical approach), and body-to-body networks (i.e., by using group mobility model). Further, IEEE 802.15.6 compliant scheduled access and CSMA/CA MAC protocols are implemented. Two $non-collaborative$ coexistence techniques (i.e., Time-shared and channel hopping) are evaluated and one *collaborative* (i.e., CSMA/CA) approach is explored. The performance is evaluated against several metrics such as PER, PRR, latency and energy consumption. It is found that for $non-collaborative$ case, channel hopping scheme performs much better under lower transmission power and should be selected for inter-body interference mitigation. Whereas, for the *collaborative* case, CSMA/CA performs very well for both delay and PRR, however, it consume energy, which could be optimized in the future by applying low power medium access approaches.

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