An Experimental Study for Inter-User Interference Mitigation in Wireless Body Sensor Networks

Bin Cao, Yu Ge, Chee Wee Kim, Gang Feng, Hwee Pink Tan, and Yun Li

***Abstract*— Inter-user interference degrades the reliability of data delivery in wireless body sensor networks (WBSNs) in dense deployments when multiple users wearing WBSNs are in close proximity to one another. The impact of such interference in realistic WBSN systems is significant but is not well explored. To this end, we investigate and analyze the impact of inter-user interference on packet delivery ratio (PDR) and throughput. We conduct extensive experiments based on the TelosB WBSN platform, considering unslotted carrier sense multiple access (CSMA) with collision avoidance (CA) and slotted CSMA/CA modes in IEEE 802.15.4 MAC, respectively. In order to mitigate interuser interference, we propose a light-weight hopping approach based on practical WBSN systems and investigate the performance in a realistic environment. Our experimental results show that the unslotted CSMA/CA is only effective in light inter-user interference scenarios. Comparably, the slotted CSMA/CA can provide dramatic performance improvement (2.7 times higher in PDR and 1.7 times higher in throughput on average), when severe inter-user interference occurs in WBSN deployment. In addition, the experimental results validate the effectiveness and correctness of our idea of a hopping approach for inter-user interference mitigation, which is based on slotted CSMA/CA mode and with low complexity.**

***Index Terms*— Wireless body sensor network, IEEE 802.15.4, interference mitigation, experimental study, hopping mechanism.**

I. Introduction

DUE to many advantages such as low power consumption, user-friendly design, and low cost, wireless sensor network (WSN) [1], [2] has been well-studied and developed into widely used wireless network for applications such as monitoring, alarm and emergency communication. As one of the emerging applications of WSN, wireless body sensor network (WBSN) [1], [2] has recently been regarded as a promising wireless platform for many human-centric applications in healthcare, fitness, assisted living and so on. Consequently, WBSN has become a hot research topic in recent years.

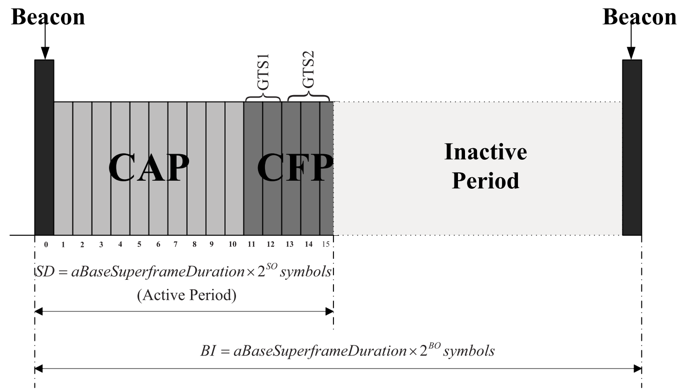

Fig. 1. Superframe in IEEE 802.15.4.

A WBSN consists of several implantable and wearable intelligent sensor nodes to gather different data from the body, and one central node, called *coordinator*, to control the data collection and schedule transmissions in the corresponding WBSN. The WBSNs can be designed by adjusting their transmission power and rate dynamically for different requirements. As one of the most widely used standards, IEEE 802.15.4 [3] can provide the time synchronization with the defined superframe mechanism, which is shown in Fig. 1 and described as follows.

In each superframe, the first signal is the Beacon, which is periodically sent by the coordinator with the information of beacon interval (BI), superframe duration (SD) and contention-free period (CFP). During the SD, nodes compete for medium access using slotted CSMA/CA in the Contention Access Period (CAP). After that, all the sensor nodes would enter the sleep mode in the inactive period.

Much research work [4], [5] has focused on the performance analysis of WBSNs in different configurations. In [4], S. Pollin *et al*. provided a detailed analytical evaluation of performance in IEEE 802.15.4 beacon-enabled star topology WBSNs, considering both saturated and unsaturated periodic traffic for acknowledgement based uplink. Their analysis is based on Markov model, similar to Bianchi's work on IEEE 802.11 DCF [6]. Apart from the analysis based on beacon-

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enabled mechanisms, C. Buratti *et al*. provided a mathematical model for non-beacon enabled mode of IEEE 802.15.4 in [5]. In their configuration, upon reception of a query from the coordinator, each sensor node captures one sample of a given phenomenon and forwards it through a direct link to the coordinator.

Regardless of the assumptions made in the above analytic work, the transmission failure caused by inter-user interference is one of the most critical factors on performance deterioration in dense WBSN deployment. Therefore, a method to mitigate the inter-user interference and improve the performance of WBSN systems becomes a valuable research topic. In order to deal with the inter-user interference among WBSNs, some interference mitigation methods have been proposed in the literature. As discussed previously, the existing work [7], [8] on inter-user interference mitigation mainly focused on the PHY/MAC layers. One of the corresponding work on PHY layer is [7], where W. Yang *et al*. provided several inter-user interference mitigation schemes based on adaptive modulation, adaptive data rate and duty cycling for WBSNs, respectively. In [8], B. S. Ramanjaneyului *et al*. designed two schemes, called selective retransmissions and sequence rearrangement, to mitigate inter-user interference. The basic idea of the proposed schemes is prioritized adaptive frequency hopping.

Although all of the above work has been well evaluated and validated with computer simulations, the performance of a realistic WBSN system is lacking. In order to investigate the performance in practical systems, some experimental work [9]–[11] have been performed. In [9], Ganesan *et al*. investigated the complex behaviors with a large-scale empirical study and revealed that even a simple protocol as flooding can exhibit surprising complexity at certain scales. In [10], the impact of transmission power on link quality had been investigated with experiments, and a transmission power control mechanism was proposed, in which blacklisting method was incorporated to enhance link reliability and minimize interference. In [11], link layer behaviors had been investigated by placing nodes on the body. The measurement data was analyzed to reveal several link layer characteristics and to derive the generic routing performance.

The fore-mentioned work investigated and evaluated important metrics in WSNs or WBSNs, and some meaningful insights have been provided in their research. However, the effect of inter-user interference among WBSNs on the performance is still missing in practical systems. The most relevant work which focused on this issue was reported in [12]. In this paper, the authors conducted a preliminary investigation of the impact of inter-user interference with a simple configuration, and then proposed a solution to deploy a fixed network infrastructure to monitor and identify WBSNs that are likely to interfere with each other. Although [12] has shown some experimental results on the effect of inter-user interference, the scenarios are static and simple such that the results are insufficient to properly understand and analyze the effect of inter-user interference in practical environments. To this end, we carefully design our experiments to observe such effects and insightfully analyze the factors that can impact performance such as movement patterns. Furthermore, we propose a hopping approach as a reference method for inter-user interference mitigation, and implement this approach on the practical WBSN system based on slotted CSMA/CA. The experimental results validate that the hopping approach can effectively mitigate inter-user interference in realistic system with very low complexity.

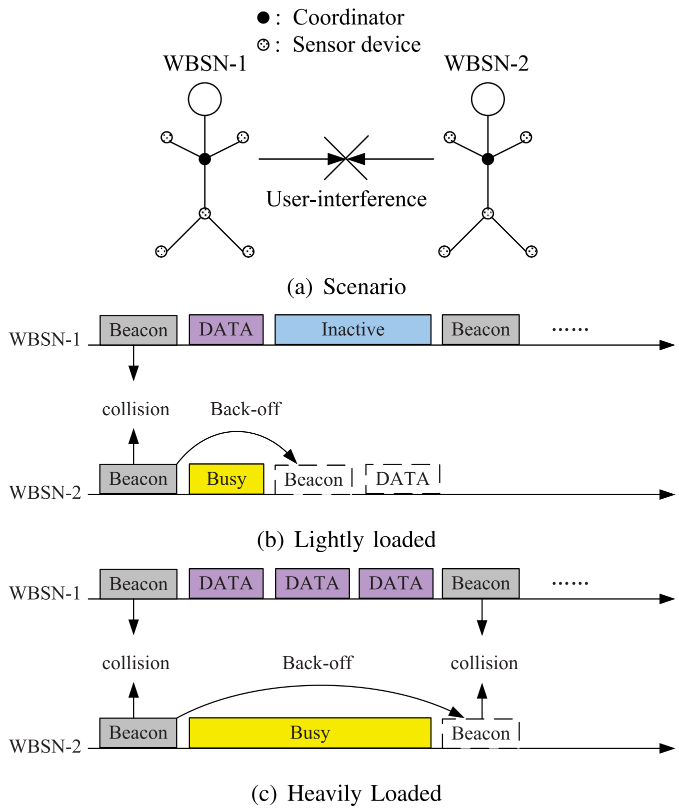


Fig. 2. An example for inter-user interference.

The rest of the paper is organized as follows. We describe the motivation of this paper and inter-user interference model in Section II. In Section III, the idea of hopping approach to mitigate inter-user interference in WBSNs is then proposed. The experimental configurations are summarized in Section IV. In Section V, we present the WBSN performance benchmark through experimental study, and the experimental results in multiple static and dynamic deployment scenarios are shown in Section VI. Finally, we conclude this paper in Section VII.

II. Motivation

With one WBSN on its own, a coordinator can perform the role of data collection and transmission scheduling with few issues. However, problems can arise in practical deployments where there are more than one person wearing WBSNs, e.g. in public areas such as hospital, nursing home, meeting room, and fitness club. Let us use an example shown in Fig. 2 to illustrate this problem.

In Fig. 2(a), there are two persons wearing WBSNs in close proximity, and the inter-user interference between the two WBSNs cannot be avoided by their coordinators if they use the same channel for transmission. When the interference or collision is detected, the two coordinators can schedule the beacon transmission with back-off mechanism for an idle period to mitigate the inter-user interference, this situation is shown in Fig. 2(b). However, this method might be ineffective if the network is heavily loaded, because there is no idle period and the performance would decline due to the intense competition, as depicted in Fig. 2(c).

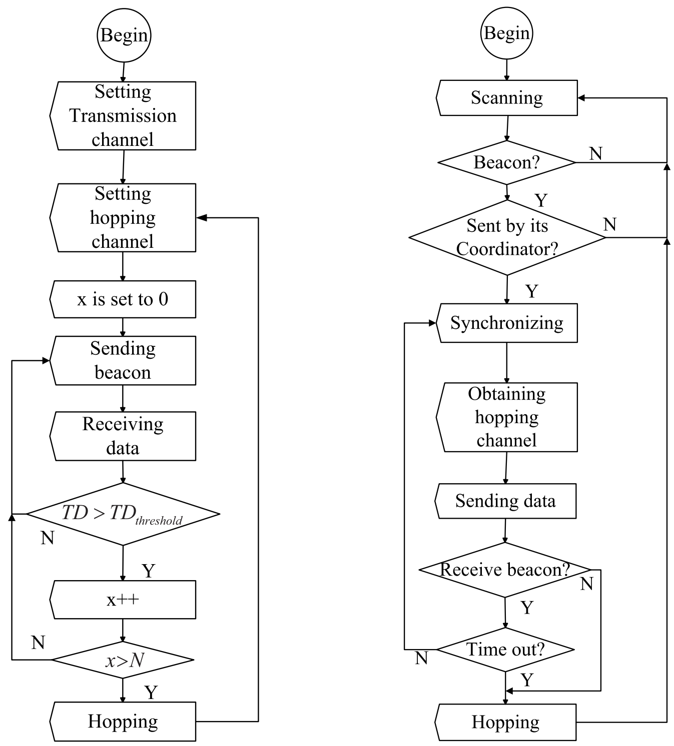
In order to mitigate inter-user interference to achieve better performance, research has been conducted for performance evaluation and improvement in multi-user environments. However, as most of the existing studies in the literature were based on computer simulations, the impact of inter-user interference on the practical WBSN system has not been well explored. In particular, the exact performance of multiple co-existing WBSNs scenarios has not been extensively evaluated, well surveyed and insightfully analyzed by the existing work, which is a very critical issue and motivates us to conduct this research.

The worst-case inter-user interference has been well discussed in previous work [13]. However, the existing interference models were based on 2-dimensional interference propagation pattern without body-centric considerations, such as orientation and body blockage. Our experimental results (see Figure 5) also indicate that human body can partially block inter-user interference, and hence the earlier 2-dimensional interference models are not applicable in the body-centric context. To fill in this gap, we first study the inter-user interference for WBSN on practical system with experimental approach and then we will extend this work to form proper theoretical models.

In this paper, we investigate the impact of inter-user interference on the performance of WBSNs in terms of PDR and throughput with an experimental approach. The main contributions of this paper are as follows. First, we propose a low-cost hopping approach to mitigate inter-user interference for realistic systems. Second, we establish performance benchmarks of realistic WBSNs as a guideline to evaluate the WBSN performance in complicated multi-user environments. Third, we evaluate the performance of hopping approach through comparison with that of unslotted CSMA/CA and slotted CSMA/CA modes in IEEE 802.15.4 MAC at different severity levels of inter-user interference. And lastly, we analyzed thoroughly the results obtained from extensively conducted experiments to show the effects of inter-user interference on performance in various practical deployment scenarios.

III. Channel Hopping Mechanism

In this section, we describe our proposed hopping approach based on beacon-enabled MAC mechanism (e.g., IEEE 802.15.4). As discussed earlier, inter-user interference has significant adverse effects on the performance of WBSNs. Although numerous methods have been proposed to address this issue and the corresponding improvement is obvious, most of them are based on computer simulation, and hence they did not sufficiently capture the exact effect of inter-user interference in the practical system. Furthermore, the design of an effective mechanism to mitigate inter-user interference in the realistic systems should be addressed. To this end, we propose a hopping approach with pre-allocation hopping channel based on beacon-enabled mechanism. Our hopping approach is effective but with very low complexity in implementation, so that it can be easily implemented in low-profile embedded systems. In addition, the mechanism is designed based on the existing standard IEEE 802.15.4 and backward compatible with the standard.



(a) Coordinator (b) Sensor device

Fig. 3. Flow chart of main procedure at various nodes in hopping approach.

In IEEE 802.15.4, there are 16 channels that can be used for transmission. And thus, the inter-user interference could be mitigated by channel hopping according to the status of hopping channels. When the performance of WBSNs is deteriorated by inter-user interference, it indicates that the adopted channel has high competition. Although the coordinator can detect and choose a light-loaded channel for transmission at the beginning, the adopted channel might be congested when the person wearing the WBSN moves to a dense area. Obviously, if the high competition of the adopted channel could be detected in time, WBSNs can hop to another light-loaded channel and thus the inter-user interference can be mitigated and the performance can be improved. To this end, we propose an interference-aware hopping approach to address this issue. We describe the procedures of hopping approach, at coordinator and sensor device, respectively, as follows.

1. Procedure at coordinator.

1) As shown in Fig. 3(a), the coordinator should choose a transmission channel to send beacon for synchronization and transmission. Although the selected channel is good for transmission for now, it might become congested later. In our hopping approach, to prepare channel hopping to mitigate inter-user interference in competitive situation, the coordinator would pre-set a backup channel randomly and inform the corresponding sensor devices in its WBSN.

2) The counter value, denoted by x, is a counter to record the times when transmission delay exceeds the threshold and set to zero at the beginning. The coordinator broadcasts beacon with the information of its selected hopping channel.

3) The coordinator waits for the data from sensor devices in the superframe duration. Coordinator would compare the transmission delay (TD) with the transmission delay threshold ($TD_{threshold}$, which could be pre-defined), if $TD > TD_{threshold}$, we identify that the transmission channel becomes competitive due to inter-user interference, and hence increase x. It is noteworthy that we do not consider transmission failure due to error, as it is rare happens from our observations due to short-distance and low rate transmissions in IEEE 802.15.4.

4) If x exceeds the threshold N, it indicates that the performance is deteriorated due to the adverse effect of inter-user interference and the adopted channel is not suitable for transmission any more. Therefore, the coordinator should hop to another channel to avoid the inter-user interference on the current channel.

5) The coordinator hops to the selected hopping channel, broadcasts beacons and waits for synchronization of other sensor devices. Meanwhile, the new hopping channel should be re-configured in beacons by the coordinator.

2. Procedure at the sensor device.

1) As shown in Fig. 3(b), the sensor device scans the channel to capture the beacon.

2) If a received beacon is broadcasted by the coordinator of the sensor device, the sensor device begins to synchronize and captures the information in the beacon including hopping channel. Otherwise, the sensor device discards this beacon and continues to scan.

3) The sensor device begins to send data to coordinator in the superframe duration, and waits for the next coming beacon for synchronization.

4) If the next beacon is missing, the device sensor need to scan the channel to capture the beacon again in a constraint time. When timeout occurs, it indicates that the current channel is not suitable for transmission and the coordinator has hopped to another channel to mitigate the inter-user interference, and thus the sensor device should hop to the corresponding hopping channel pre-configured by its coordinator in beacon. Otherwise, the sensor device repeats step 4 (since the beacon is missing, it cannot send data in SD duration).

To summarize, for the hopping approach, if the inter-user interference can be detected, the coordinator can change the transmission channel when the adverse effect of inter-user interference exceeds to the threshold. The only overhead is the 1 byte information of hopping channel carried by beacon and the computation time of x and TD, which is a very light operation and can be ignored. The hopping approach is simple and effective, and it is designed to be backward compatible based on IEEE 802.15.4.

IV. Experimental Setup

The configurations of our experiments for investigation of inter-user interference are as follows:

Sensor node hardware : we use TelosB motes with CC2420 radio chip in the experiments. The transmission power is fixed to 0 dBm.

Locations of on – body nodes : in a specific experiment, one or two transmitter nodes are deployed on the left and right arms, respectively; and one receiver node is deployed at right waist.

Environment : the experiments have been carried out in a meeting room with a dimension of 13 m × 13 m.

Traffic profile : each transmitter node sends data packets in 30 ms interval with a fixed payload size of 100 bytes.

Network architecture : in each WBSN, star topology is adopted in all experiments where the transmitter node sends data directly to the coordinator. All WBSNs operate at the same physical channel (Channel 26) in the beginning.

MAC modes : two MAC modes are used in IEEE 802.15.4 in the experiment, unslotted CSMA/CA[1] and slotted CSMA/CA.[2] In the unslotted CSMA/CA, clear channel access (CCA) and backoff schemes are enabled, while acknowledgment and re-transmission are disabled. In the slotted CSMA/CA, only the CAP is used in superframes in IEEE 802.15.4. The beacon order is 8 (4 second beacon period) without guaranteed time slots (GTS) and inactive period. Minimum binary exponential (BE) and maximum BE are respectively 3 and 5, maximum number of backoffs is 4, and maximum number of re-transmissions is 3. Besides, hopping approach based on slotted CSMA/CA is adopted too.

V. Performance Benchmark

In this section, we describe two sets of experiments that were conducted to evaluate the WBSN benchmark performance (Exp.1 and Exp.2 in the following subsections). In WBSNs, PDR and throughput are the two key performance metrics to indicate the transmission reliability and network capacity. In order to investigate the baseline performance of TelosB based WBSN without the effect of human body, we put all sensor nodes on table in this benchmark study. In such a case, we still use the term "WBSN", although the nodes are not deployed on the body in those experiments.

A. Benchmark Performance of TelosB WBSN (Exp. 1)

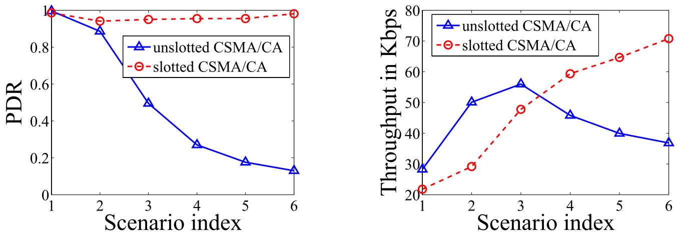
In this experiment, we investigate and compare the performance of TelosB WBSN networks in the following six scenarios:

- Scenario 1 (S_1): a single WBSN with one transmitter node and one receiver node,
- Scenario 2 (S_2): a single WBSN with two transmitter nodes and one receiver node,
- Scenario 3 to Scenario 6 (S_3 to S_6): there are 2, 3, 4 and 5 WBSNs respectively, each with two transmitter nodes and one receiver node.

We place all the transmitter nodes on one table and all the receiver nodes on another table, and the distance between a pair of transmitter node and receiver node is 60 cm. In each

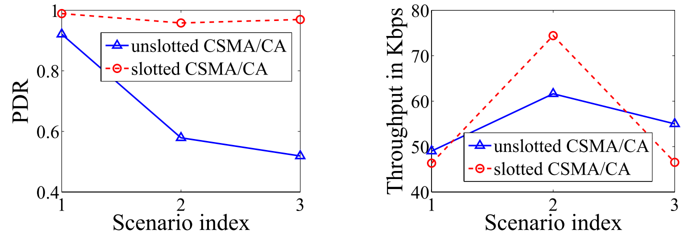
[1] Implemented in TinyOS 2.1.0 according to TEP 126.

[2] Implemented in TKN MAC by Technical University Berlin.



(a) PDR (b) Throughput

Fig. 4. Performance benchmark of TelosB based WBSN.



(a) PDR (b) Throughput

Fig. 5. Impact of body blockage on inter-user interference.

experiment, every transmitter node sends 1000 data packets to its corresponding receiver. The experimental results are shown in Fig. 4.

In Fig. 4, the comparisons of PDR and throughput between unslotted CSMA/CA and slotted CSMA/CA are shown in Figs. 4(a) and (b), respectively. Fig. 4(a) shows that unslotted CSMA/CA and slotted CSMA/CA can achieve similar PDR in Scenario 1 where the network is not saturated, while in the more heavily-loaded scenarios (S_2 to S_6), the PDR of slotted CSMA/CA is always higher than that of unslotted CSMA/CA. We also observe that the PDR of unslotted CSMA/CA decreases with more concurrent transmissions, while the PDR of slotted CSMA/CA is very stable (at 95% level), indicating that slotted CSMA/CA is robust to interference in PDR.

Correspondingly, from Fig. 4(b) we can see that in Scenarios 1, 2 and 3, the throughput of both modes increases with more concurrent transmissions and the throughput of unslotted CSMA/CA is higher than that of slotted CSMA/CA in all of the three scenarios. The reason is that the whole system in Scenarios 1, 2 and 3 is not saturated, and hence higher throughput can be achieved when more traffic is injected into the network. In such cases, although some data packets might be lost due to inter-user interference, the total number of received data packets still increases. Therefore, in Scenarios 1, 2 and 3, the throughput of unslotted CSMA/CA is increased, although the corresponding PDRs are reduced. Comparing with slotted CSMA/CA which provides acknowledgment and retransmissions, the operational overhead of unslotted CSMA/CA is low, which explains why unslotted CSMA/CA outperforms slotted CSMA/CA in throughput when the system is lightly loaded.

In Scenarios 4, 5 and 6, it can be seen that the throughput of unslotted CSMA/CA is lower than that of slotted CSMA/CA and decreases with further increase in concurrent transmissions. In contrast, the throughput of slotted CSMA/CA increases with more concurrent transmissions. Meanwhile, the PDR of unslotted CSMA/CA decreases obviously with more concurrent transmissions, while the PDR of slotted CSMA/CA is stable. In those scenarios, as the system becomes heavily loaded, the contention and collision caused by inter-user interference reach a high level, which affects the throughput and PDR of unslotted CSMA/CA. In contrast, slotted CSMA/CA is designed to be able to detect inter-user interference more reliably using two-slot channel sensing approach, and hence can better avoid the interference. As a result, slotted CSMA/CA significantly outperforms unslotted CSMA/CA in both throughput and PDR when the system is heavily loaded.

B. Impact of Body Blockage on Inter-User Interference (Exp.2)

When a WBSN is deployed on body, the radio signals transmitted from other WBSNs may be partially blocked by the bodies of WBSN users, and hence the interfering signals may be attenuated when they reach the coordinators. The purpose of this experiment is to investigate how the human body blocks interfering signals between two WBSNs and affects their performance. To obtain the baseline performance, we first place two WBSNs on two tables respectively, and the distance between the two tables (WBSNs) is 60 cm. Each WBSN has two transmitter nodes and one receiver node. We conduct experiments in the following three scenarios:

- Scenario 1 (S_1): only one WBSN is active,
- Scenario 2 (S_2): two WBSNs are active and a person stands between the two tables to block the two WBSNs. In such a case, the two WBSNs are non-line-of-sight of each other,
- Scenario 3 (S_3): this scenario is similar to S_2, except that there is no human blockage between the two WBSNs.

Fig. 5 shows the performance comparison of unslotted CSMA/CA and slotted CSMA/CA in the above three scenarios. Similar to the results shown in Fig. 4(a), the PDR with slotted CSMA/CA is stable (at 95% level) and robust to inter-user interference in all scenarios. In unslotted CSMA/CA mode, obviously, the highest PDR can be achieved when there is only one active WBSN as there is no inter-user interference from other WBSN. When two WBSNs are active simultaneously, the achieved PDR with the presence of body blockage is higher than that without body blockage, which indicates that body blockage can obviously mitigate the adverse impact of inter-user interference.

The total throughput of WBSNs with unslotted CSMA/CA and slotted CSMA/CA are shown in Fig. 5(b) for each scenario. It can be seen that, in both modes, the system throughput can achieve the highest value when two WBSNs are blocked by body. Without body blockage, the system throughput is only 60% and 85% of that with the presence of body blockage in slotted CSMA/CA and unslotted CSMA/CA, respectively. Furthermore, slotted CSMA/CA outperforms unslotted CSMA/CA in throughput in this experiment, as the scheduling procedure in slotted CSMA/CA can effectively decrease the adverse impact of inter-user interference.

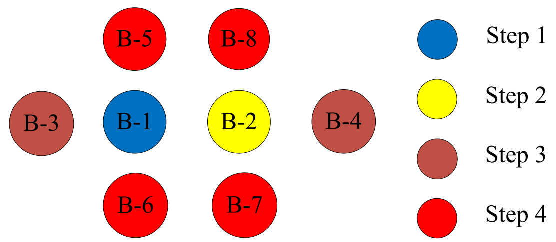


Fig. 6. Line static (LS) scenario.

In summary, the experimental results of both PDR and throughput indicate that human body can partially block inter-user interference, so that the adverse impact of such interference can be mitigated. In indoor multipath environments, it is hard to achieve complete blockage of interference such that two close-by WBSNs can operate without interfering each other. If such an ideal case (complete blockage of interference) exists, the PDR in S_2 will be the same as that in S_1, while the throughput in S_2 will be double of that in S_1.

The experiments described in this section focus on the investigation of baseline performance of the realistic WBSN system without the impact of on-body deployment. Such results can provide basic performance indications of such systems for our further investigation. In the subsequent section, we conduct extensive experiments to study the impact of inter-user interference in realistic on-body deployments.

VI. Impact of Inter-User Interference in Realistic On-Body Deployments

From the results shown in Fig. 5, body blockage can partially mitigate inter-user interference. In this section, we conduct extensive experiments to study the impact of inter-user interference on WBSN performance, which include the following scenarios:

- Face to face (f2f) scenario: there are two WBSN users (B-1 and B-2) in this experiment, and each user wears two transmitter nodes (on both arms) and one receiver node (at right waist). The two users face each other during the experiment.
- Back to back (b2b) scenario: similar to f2f scenario, except that the two users have back-to-back positions during the experiment.
- Line static (LS) scenario: there are eight WBSN users (B-1 to B-8) in this experiment, and each user wears one transmitter node (on left arm) and one receiver node (at right waist). The eight WBSN users sit in three rows, as shown in Fig. 6.
- Random movement (RM) scenario: there are eight WBSN users (B-1 to B-8) in this experiment, and each user wears one transmitter node (on left arm) and one receiver node (at right waist). The users randomly move in the room during the experiment.

A. Performance of f2f and b2b Scenarios (Exp. 3)

1) Procedures of Experiments: In the f2f scenario, B-1 stands still, back towards the wall and facing B-2. B-1 maintains the same posture and B-2 moves during the experiment duration (180 seconds). The experimental procedure is divided into six steps as follows:

- Step 1 (0-30 seconds): B-2 stands 10 meters away from B-1. B-1 begins to transmit data while B-2 is inactive.
- Step 2 (30-60 seconds): both B-1 and B-2 transmit data while keeping static standing posture.
- Step 3 (60-90 seconds): B-1 maintains the same posture while B-2 slowly walks towards B-1 until their distance is 0.5 meter; both of them transmit data.
- Step 4 (90-120 seconds): B-1 and B-2 maintain standing posture with the distance of 0.5 meter; both of them transmit data.
- Step 5 (120-150 seconds): B-2 moves away from B-1 slowly until their distance is 10 meters again, facing B-1 during his walk; both of them transmit data.
- Step 6 (150-180 seconds): B-2 stands still and transmits data, while B-1 is inactive.

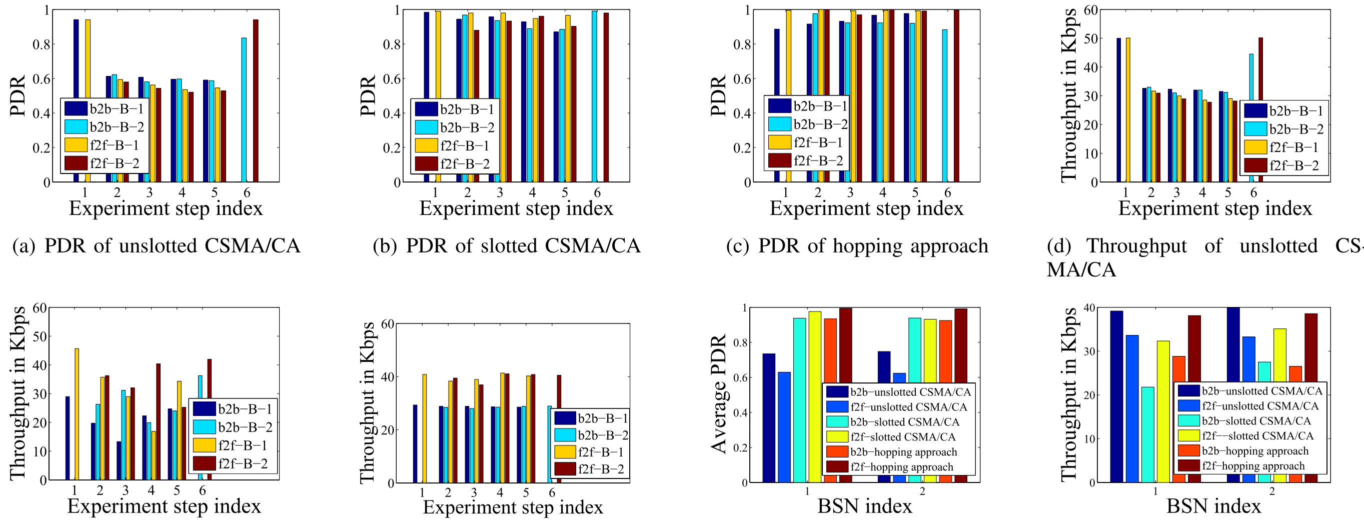
It is noteworthy that both of B-1 and B-2 face each other in the whole experiment.

In the b2b scenario, the experimental procedure is similar to that in f2f, expect that B-1 stands facing the wall and the two users are back to back during the experiment.

2) Performance Results in f2f and b2b Scenarios: The comparison of PDR and throughput with unslotted CSMA/CA, slotted CSMA/CA and hopping approach are shown in Fig. 7. The corresponding PDR in each step and average PDR for the whole duration are plotted in Figs. 7(a)–(f). In the f2f experiment, the PDR of B-1 with unslotted CSMA/CA is 0.94 in Step 1 and decreases to around 0.55 in Steps 2, 3, 4 and 5. The reason is that B-1 can transmit data without inter-user interference in Step 1, while in Steps 2 to 5, multiple users share the wireless channel and the inter-user interference occurs. Similarly, in unslotted CSMA/CA mode, the PDR of B-2 in Step 6 is higher than that in Steps 2 to 5. In contrast, the PDRs with slotted CSMA/CA and hopping approach are stable (mostly at 90% level) and robust to inter-user interference.

The observed patterns from the b2b experimental results are similar to those of f2f except the throughput in slotted CSMA/CA and hopping approach. In addition, it can be seen that, in unslotted CSMA/CA mode, the PDR of b2b scenario is higher than that in f2f scenario in general. The reason is that the body blockage of interference in b2b scenario is more severe than that in f2f scenario, and hence the adverse impact of interference can be further mitigated in b2b scenario as compared to f2f scenario. Such observation confirms the results shown in subsection V.B.

Although slotted CSMA/CA significantly outperforms unslotted CSMA/CA in PDR, the throughput of slotted CSMA/CA is lower than expected. In the f2f experiment, we can see that the average throughput of B-1 and B-2 with unslotted CSMA/CA is 33.5 kbps and 33.2 kbps, respectively. The corresponding throughput is very close to that with slotted CSMA/CA, which are 32.3 kbps and 35.1 kbps in B-1 and B-2, respectively. Surprisingly, we observe that, in b2b scenario, unslotted CSMA/CA outperforms slotted CSMA/CA in the average throughput of



(a) PDR of unslotted CSMA/CA (b) PDR of slotted CSMA/CA (c) PDR of hopping approach (d) Throughput of unslotted CSMA/CA

(e) Throughput of slotted CSMA/CA (f) Throughput of hopping approach (g) Average PDR (h) Average Throughput

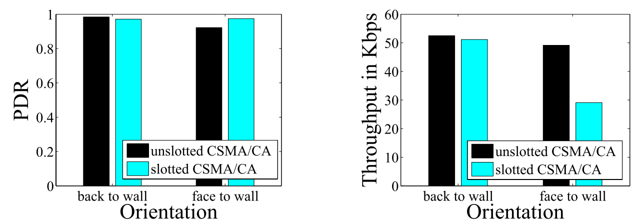
Fig. 7. Impact of orientation.

B-1 and B-2, where the slotted CSMA/CA only achieves 21.8 kbps (B-1) and 27.5 kbps (B-2), much lower than unslotted CSMA/CA (33.6 kbps for B-1 and 33.3 kbps for B-1). Furthermore, the average throughput with slotted CSMA/CA in b2b experiment is lower than that in f2f experiment. Such results are in contrast to our observations from Fig. 5(b), where slotted CSMA/CA achieves higher throughput than unslotted CSMA/CA with the presence of body blockage. Moreover, although hopping approach based on slotted CSMA/CA outperforms slotted CSMA/CA in throughput because the former can hop to another idle channel to mitigate the adverse effect of inter-user interference, the corresponding performance of throughput is also lower than that of unslotted CSMA/CA especial in f2f scenario.

Considering B-1 always stands near the wall (with 0.6 meter distance) in the experiment, in order to investigate the above mentioned unexpected result, we conduct an additional experiment to evaluate the impact of multi-path effect from the wall on WBSN performance.

3) Impact of Multi-Path Effect From the Wall on Performance Results in f2f and b2b Scenarios (Additional Exp. 4): In this experiment, a person, wearing two transmitter nodes and one receiver node, stands still with his face/back towards the wall, respectively. Considering hopping approach is based on slotted CSMA/CA, we just focus on the investigation of unslotted CSMA/CA and slotted CSMA/CA in this experiment. The corresponding experimental results are shown in Fig. 8.

As expected, the PDR results match the results shown in Fig. 5(a). However, the results shown in Fig. 8(b) reveal that the orientation (face/back towards the wall) significantly affects the throughput performance of slotted CSMA/CA but only has slight impact on that of unslotted CSMA/CA. The reason is that the reflected signals from the wall interfere with the signals from the direct transmissions over on-body links which is hard to be detected at the transmitter node, and such interference is more severe when the user faces the wall as



(a) PDR (b) Throughput

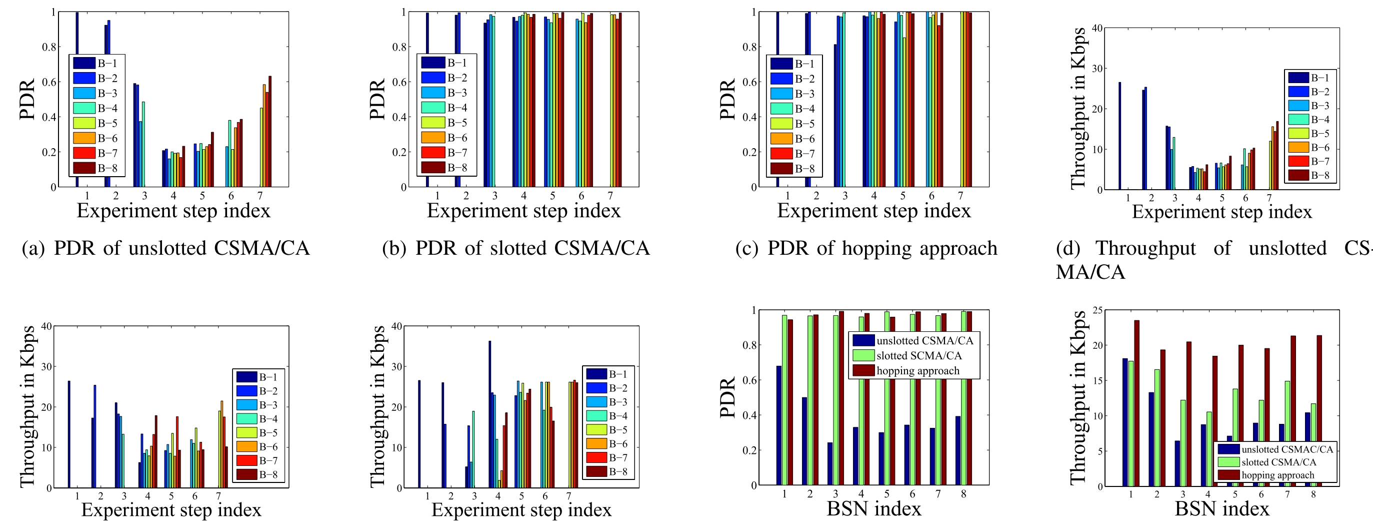
Fig. 8. Impact of the multipath effect from the wall.

compared to the scenario when he stands with back towards the wall. In slotted CSMA/CA, such multipath effect may cause the loss of beacons in a superframe, which in turn leads to not being able to transmission in this superframe. In such a case, the throughput will be decreased. This is confirmed by the observations that no data received in some superframes in the experiments. The results in the additional experiment confirm and explain the unexpected results in Section VI A.(2), in that in b2b scenario, unslotted CSMA/CA outperforms slotted CSMA/CA in the average throughput. The reason is that strong multipath effect leads to significant beacon loss, which in turn leads to null transmission in the corresponding superframe and reduced throughput.

B. Performance of LS Scenario (Exp. 5)

The purpose of this experiment is to investigate the impact of inter-user interference on performance incurred by line static of a group of people wearing WBSNs. In this experiment, eight users (B-1 to B-8) in the meeting room which is shown in Fig. 6, each wearing one transmitter node (on left-arm) and one receiver node (at right waist). The experiment duration is 210 seconds, divided into seven steps as follows:

- Step 1 (0-30 seconds): B-1 begins to transmit data and others keep silence.
- Step 2 (30-60 seconds): B-2 wakes up and transmits data.



(a) PDR of unslotted CSMA/CA (b) PDR of slotted CSMA/CA (c) PDR of hopping approach (d) Throughput of unslotted CSMA/CA

(e) Throughput of slotted CSMA/CA (f) Throughput of hopping approach (g) Average PDR (h) Average Throughput

Fig. 9. Impact of interference in line static scenario.

- Step 3 (60-90 seconds): B-3 and B-4 wake up and begin to transmit data.
- Step 4 (90-120 seconds): B-5, 6, 7 and 8 wake up and begin to transmit data. In this step, all eight users transmit data.
- Step 5 (120-150 seconds): B-1 stops transmission.
- Step 6 (150-180 seconds): B-1 and B-2 stop transmission.
- Step 7 (180-210 seconds): B-1, 2, 3 and 4 stop transmission. The experiment stops at 210 seconds.

The throughput results in Fig. 9 appear U shape patterns with regard to time. This implies that the severity of interference has direct impact on performance as the interference tends to be more severe in the middle steps of experiment as compared to the starting and ending steps.

From Figs. 9(a) and (d), we observe that, in each step, both PDR and throughput in unslotted CSMA/CA mode are similar among all active users, and hence all active users share the bandwidth in a fair way in unslotted CSMA/CA mode. However, this is not true in slotted CSMA/CA where sharing of bandwidth among active users show random patterns in each step (see Fig. 9(e)). This is probably caused by the random loss of beacons in slotted CSMA/CA. In such a case, the transmitter, when not receiving the beacon, is unable to transmit in that superframe. Besides, we can see that the throughput differences among BSNs in hopping approach are significant (see Fig. 9(f)). As the throughput of WBSNs is different due to random beacon loss in slotted CSMA/CA, each WBSN may decide channel hopping in different steps.

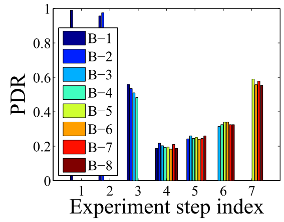
We then measure the PDR and throughput performance for each user; the results are shown in Figs. 9(g) and (h). It can be seen that, in unslotted CSMA/CA mode, B-1 achieves the best performance as it utilizes the channel alone in Step 1 while all other users have to compete with their peers during the whole experiment period. The performance of B-2 is better than others except B-1, as it only needs to compete with B-1 in Step 2. Compared to B-1 and B-2, the remaining users (B-3 to B-8) show similarly worse performance, as they have to compete with at least three users for their transmissions during their active time. Such observations conform to the benchmark performance as shown in Fig. 4. We also observe that the deployment location of nodes have impact on the performance of WBSNs. For example, the throughput of B-3 is the lowest. The reason is that the receiver of B-3 (on the right waist) is with line-of-sight of all other transmitters (on the left arm) without body blockage (see in Fig. 5), and hence the B-3 receiver incurs the most severe interference. This result conforms the benchmark performance as shown in Fig. 5.

Due to the same above-mentioned reason, the trend of throughput performance of the users in slotted CSMA/CA is similar to that of unslotted CSMA/CA (see Fig. 9(h)). The lower throughput of both B-5 and B-7, as compared to others (except B-1 and B-2), is probably caused by the random loss of beacons and random backoff schemes adopted by slotted CSMA/CA when contention or collision occurs.

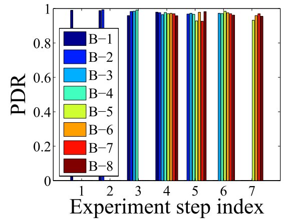
We can also find that hopping approach can significantly improve the performance of WBSNs, and the corresponding performance of WBSNs is more stable than that of both unslotted and slotted CSMA/CA. The reason is obvious that hopping to other idle channels can effectively mitigate the inter-user interference. As expected from our earlier results, the users can achieve stable PDR (at 95% level) in slotted CSMA/CA and hopping approach which is based on slotted CSMA/CA, regardless of the amount of competing users (see Fig. 9(g)). Such a result further confirms that the slotted CSMA/CA is robust to inter-user interference.

C. Performance of Random Movement Scenario (Exp. 6)

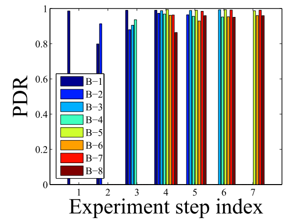
The purpose of this experiment is to investigate the impact of inter-user interference on performance incurred by random movement of a group of people wearing WBSNs. In this experiment, eight users (B-1 to B-8) walk randomly in the meeting room, each wearing one transmitter node (on left-arm) and one receiver node (at right waist).The experiment duration



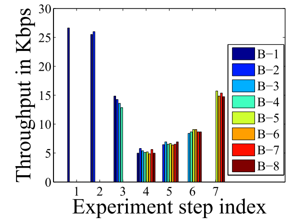
(a) PDR of unslotted CSMA/CA



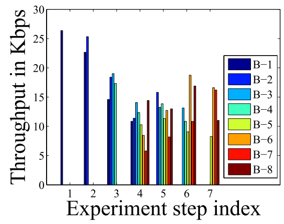
(b) PDR of slotted CSMA/CA.



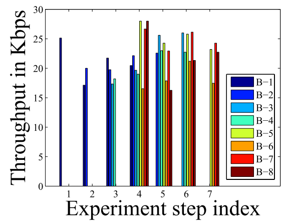
(c) PDR of hopping approach.



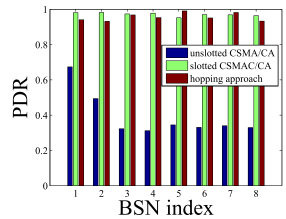
(d) Throughput of unslotted CSMA/CA.



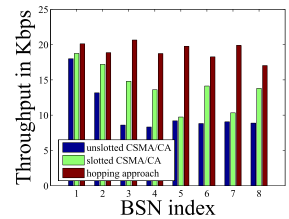
(e) Throughput of slotted CSMA/CA.



(f) Throughput of hopping approach.



(g) Average PDR



(h) Average Throughput

Fig. 10. Impact of interference in random movement scenario.

is 210 seconds, the same as that in experiments 5 and 6, and the experimental results are shown in Fig. 10.

In this experiment, when users walk randomly, we measure the PDR and throughput in each step as well as for the whole experiment, with unslotted CSMA/CA, slotted CSMA/CA and hopping approach. In Figs. 10(a), (b) and (c), we can see that the PDR of both slotted CSMA/CA and hopping approach outperform that of unslotted CSMA/CA, while the hopping approach has slightly lower throughput than that of slotted CSMA/CA. In Figs. 10(d), (e), and (f), it is observed that the throughput of unslotted CSMA/CA is low but fair among all users. Comparably, the hopping approach achieves higher throughput than other two schemes. As shown in Figs. 10(g) and (h), the hopping approach achieves 144% and 164% higher throughput, as compared to slotted CSMA/CA and unslotted CSMA/CA, respectively.

D. Discussions

The worst-case inter-user interference model was studied in [13] and the path-loss radio propagation model is given as follows,

$$P_{rx} = \frac{P_{tx}}{R^{\theta}}, \tag{1}$$

where P_{rx}, P_{tx}, R and θ is the transmission power at transmitter, the received signal strength at receiver, the distance between the transmitter and the receiver, and the path loss exponent (generally from 2–4) [14], respectively.

According to [13], the worst-case inter-user interference (I) is given as follows,

$$I = \frac{2P_{tx}}{(D-R)^{\theta}} + \frac{P_{tx}}{(D-\frac{R}{2})^{\theta}} + \frac{P_{tx}}{D^{\theta}} + \frac{P_{tx}}{(D+\frac{R}{2})^{\theta}} + \frac{P_{tx}}{(D+R)^{\theta}}, \tag{2}$$

where D is the carrier sense range.

Based on I, the worst-case Signal Interference Noise Ratio (SINR) can be calculated according to [13] as follows,

$$\begin{aligned} SINR &= \frac{\frac{P_{tx}}{R^{\theta}}}{\frac{2P_{tx}}{(D-R)^{\theta}} + \frac{P_{tx}}{(D-\frac{R}{2})^{\theta}} + \frac{P_{tx}}{D^{\theta}} + \frac{P_{tx}}{(D+\frac{R}{2})^{\theta}} + \frac{P_{tx}}{(D+R)^{\theta}}} \\ &= \frac{1}{\frac{2}{(\frac{D}{R}-1)^{\theta}} + \frac{1}{(\frac{D}{R}-\frac{1}{2})^{\theta}} + \frac{1}{(\frac{D}{R})^{\theta}} + \frac{1}{(\frac{D}{R}+\frac{1}{2})^{\theta}} + \frac{1}{(\frac{D}{R}+1)^{\theta}}}. \end{aligned} \tag{3}$$

The worst-case SINR indicates the impact of position on the inter-user interference, and the SINR is correlated with PDR and throughput. However, the existing interference models were based on 2-dimensional interference propagation pattern without body-centric considerations, such as orientation and body blockage, and this observation has been investigated by our experimental results. Therefore, the earlier 2-dimensional interference models are not applicable in the body-centric context. To this end, we first study the inter-user interference for WBSN on practical system with experimental approach and then we will extend this work to form proper theoretical models. It is obvious that system parameters have certain effects on performance. We summarize such effects as follows:

- Effect of transmission power: The transmission power supported by the system is −24∼0 dBm. The higher the transmission power, the higher the Received Signal Strength Indicator (RSSI), and hence the wireless link is more robust and the throughput and PDR tends to be higher. In contrast, the throughput and PDR would be declined when transmission power is decreased. When the transmission power is low, the main reason of packet loss is the blockage of human body. In comparison, when the transmission power is sufficiently high, the packets loss is mainly due to inter-user interference.
- Effect of duty cycle: According to our previous work [15], we find that the Packet Error Rate (PER) increases with the duty cycle. The reason is that when the duty cycle

gets higher more BSNs transmit simultaneously resulting in higher PER.

- Effect of superframe duration: In the beacon-enabled mode, if the superframe has longer duration (the larger beacon order), we observe the throughput may drop in congestion situation due to not being able to transmit in a long period of time because of beacon loss. In contrast, when the superframe has shorter duration (the smaller beacon order), the beacon loss has less significant effect on throughput, but the system overhead is higher due to processing of beacon information. Therefore, the beacon order must be carefully selected to optimize performance.

VII. Conclusion

In this paper, we investigated the impact of inter-user interference on WBSNs performance through extensive experiments. Our experimental results confirm the adverse effect of inter-user interference on WBSN performance and hence the importance of inter-user interference mitigation. In addition, we found that slotted CSMA/CA generally outperforms unslotted CSMA/CA when the wireless channel is heavily loaded by inter-user interference; but the slotted CSMA/CA also compromises throughput due to beacon loss. Furthermore, we have interesting findings on human-related impact factors, such as body blockage, deployment orientation, and movement patterns, which have significant effects on the performance. In order to mitigate the inter-user interference, we also propose a simple but effective hopping approach and implement it in practical system. The experimental results have validated the correctness and effectiveness of the proposed hopping approach. We believe that our results can provide practical engineering insights and can be used as a reference for WBSN system design. Nevertheless, considering the data loss during the hopping transition, one future work is to improve the hopping approach in this aspect.

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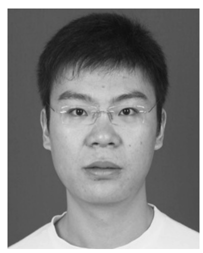

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