Investigating the Impact of Inter-User Interference in Wireless Body Sensor Networks: an Experimental Approach

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***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 has not been well explored. To this end, we investigate and analyze the impact of inter-user interference in practical WBSN systems based on TelosB platform. We capture packet delivery ratio (PDR) and throughput considering unslotted carrier sense multiple access with collision avoidance (unslotted CSMA/CA) and slotted CSMA/CA modes in IEEE 802.15.4 MAC. 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.**

***Index Terms*—wireless body sensor network, IEEE 802.15.4, interference, medium access control, experimental study.**

I. INTRODUCTION

Wireless body sensor network (WBSN) [1][2] has recently been regarded as a promising wireless platform for many human-centric applications in healthcare, fitness monitoring, assisted living and so on. Due to its advantages such as low power consumption, user-friendly design, and low cost, WBSN has become a hot research topic in recent years.

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. In practical deployments, usually multiple people wear WBSNs in a certain public area such as hospital, nursing home, meeting room, and fitness club. In such cases, inter-user interference among WBSNs will be present when more than one WBSNs operate in the same wireless channel. Although a coordinator can schedule the transmissions to provide reliable communications for its own WBSN, it is hard to coordinate the transmissions among other WBSNs. Moreover, a WBSN may randomly emerge or disappear due to the mobility of the user, and it is hard to deploy a central controller on demand for the whole WBSNs system to coordinate and schedule transmissions. As a result, inter-user interference is unavoidable when multiple WBSNs coexist in a confined area.

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.

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 establish performance benchmarks of realistic WBSNs as a guideline to evaluate the WBSN performance in complicated multi-user environments. Second, we compare the performance between unslotted CSMA/CA and slotted CSMA/CA modes in IEEE 802.15.4 MAC at different severity levels of inter-user interference. Finally, we conduct extensive experiments to show the effects of inter-user interference on performance in various practical deployment scenarios and analyze the experimental results extensively.

The rest of the paper is organized as follows. In Section II, we survey and discuss the related work. The experimental configurations are summarized in Section III. In Section IV, we present the WBSN performance benchmark through experimental study, and the experimental results in multiple static and dynamic deployment scenarios are shown in Section V. Finally, we conclude this paper in Section VI.

II. RELATED WORK

Much research work [3][4] has focused on the performance analysis of WBSNs in different configurations. In [3], 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

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based on Markov model, similar to Bianchi′s work on IEEE 802.11 DCF [5]. Apart from the analysis based on beacon-enabled mechanisms, C. Buratti *et al.* provided a mathematical model for non-beacon enabled mode of IEEE 802.15.4 in [4]. 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.

In order to deal with the inter-user interference among WBSNs, some interference mitigation methods have been proposed in the literature. As we discussed previously, the existing work [6][7] on inter-user interference mitigation mainly focused on the PHY/MAC layers. One of the corresponding work on PHY layer is [6], 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 [7], 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 [8][9] have been performed. In [8], the impact of transmission power on link quality has been investigated with experiments, and a transmission power control mechanism was proposed, incorporated blacklisting method to enhance link reliability and minimize interference. Link layer behaviours have been investigated [9] 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 [10]. 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 that paper 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.

III. EXPERIMENTAL SETUP

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

$Sensor\ node\ hardware$: TelosB motes are used with CC2420 radio chip with fixed 0 dBm transmission power.

$Locations\ of\ on-body\ nodes$: 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 10 m x 10 m.

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

$Network\ architecture$: 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).

$MAC\ modes$: two IEEE 802.15.4 MAC modes are used in the experiments, unslotted CSMA/CA[1], and slotted CSMA/CA[2]. In unslotted CSMA/CA, clear channel access (CCA) and backoff schemes are enabled, while acknowledgment and re-transmission are disabled. The slotted CSMA/CA is employed in the contention access period (CAP) of the superframe in IEEE 802.15.4. The beacon order is 8 (4 second beacon period) without guaranteed time slots (GTS) and inactive period. Minimum BE and Maximum BE are 3 and 5 respectively, maximum number of backoffs is 4, and maximum number of re-transmissions is 3.

IV. WBSN PERFORMANCE BENCHMARK

In this section, we present two sets of experimental results to evaluate the WBSN benchmark performance (Exp.1 and Exp.2). 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 the sensor nodes on the plastic 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, 5) WBSNs, each with two transmitter nodes and one receiver node. The experimental results are shown in Fig.1.

In Fig.1, the comparisons of PDR and throughput between unslotted CSMA/CA and slotted CSMA/CA are shown in Figs.1 (a) and (b), respectively. Fig.1 (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. Correspondingly, from Fig.1 (b) we can see that

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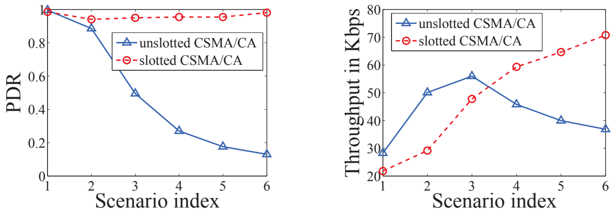
[1] Implemented in TinyOS 2.1.0 according to TEP 126.

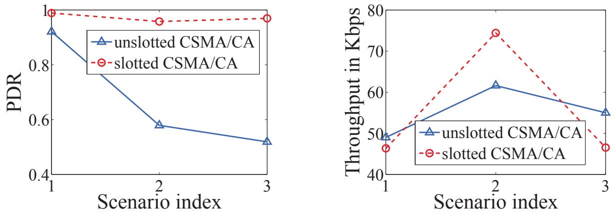
[2] Implemented in TKN MAC by Technical University Berlin.



(a) PDR

(b) Throughput

Fig. 1. Performance benchmark of TelosB based WBSN.



(a) PDR

(b) Throughput

Fig. 2. Impact of body blockage on inter-user interference.

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. 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.

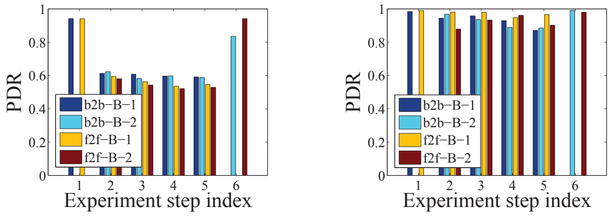
B. Impact of body blockage on inter-user interference (Exp.2)

The purpose of this experiment is to investigate how the human body blocks the interfering signals between two WBSNs and affects their performance. 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 WBSNs to block them. 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.2 shows the performance comparison of unslotted CSMA/CA and slotted CSMA/CA in the three scenarios. In Fig.2 (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. In Fig.2 (b), 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 modes, 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.

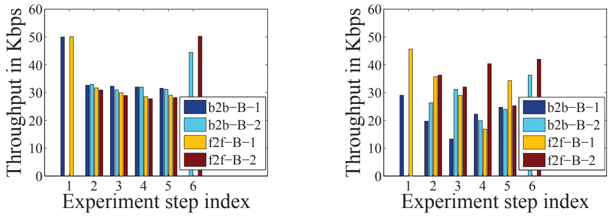
V. IMPACT OF INTER-USER INTERFERENCE IN REALISTIC ON-BODY DEPLOYMENTS

From the results shown in Fig. 2, 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. Random movement 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).



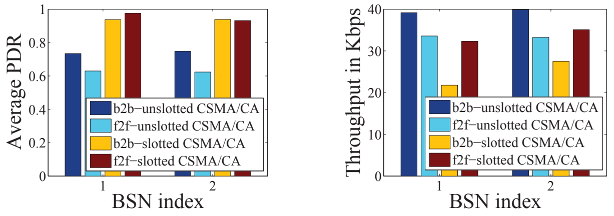
(a) PDR of unslotted CSMA/CA

(b) PDR of slotted CSMA/CA



(c) Throughput of unslotted CSMA/CA

(d) Throughput of slotted CSMA/CA



(e) Average PDR

(f) Average Throughput

Fig. 3. Impact of orientation.

A. Performance of face-to-face and back-to-back 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: (1) 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, (2) Step 2 (30-60 seconds): both B-1 and B-2 transmit data while keeping static standing posture, (3) 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, (4) 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, (5) 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, (6) 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 and slotted CSMA/CA are shown in Fig.3. The corresponding PDR in each step and average PDR for the whole duration are plotted in Figs.3 (a)-(d). 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 PDR with slotted CSMA/CA is stable (mostly at 90% level) and robust to inter-user interference.

The observed patterns from the b2b experimental results are similar to that of f2f. 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 is lower in b2b scenario as compared to f2f scenario. Such observation confirms the results shown in subsection IV.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 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. 2 (b), where slotted CSMA/CA achieves higher throughput than unslotted CSMA/CA with the presence of body blockage.

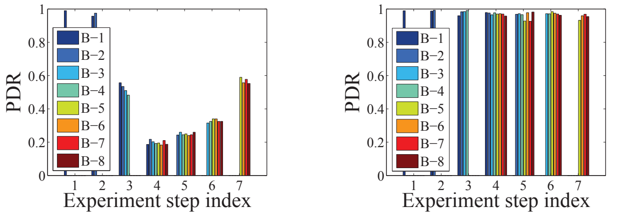
Considering B-1 always stands near the wall in the experiment, in order to investigate the above mentioned unexpected result, we conduct an additional experiment to evaluate the impact of multi-path effect on WBSN performance. In this experiment, a WBSN wearer stands still with his face/back towards the wall, respectively. We observe that the orientation 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 of the direct transmissions, and such interference is more severe when the user faces the wall as compared to the scenario when he stands with back towards the wall. In slotted CSMA/CA, such multipath induced fading may cause the loss of beacon in a superframe, which in turn leads to not being able to transmission in that superframe and hence the throughput is decreased by 40% in f2f scenario, which is confirmed by the observations that no data received in some superframes in the experiments.

B. Performance of random movement scenario (Exp. 4)

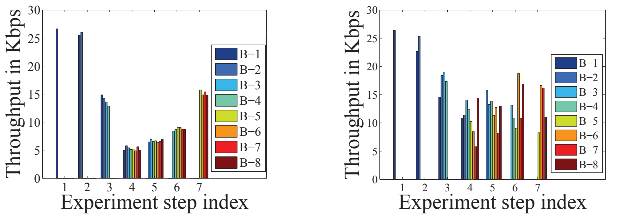
The purpose of this experiment is to investigate the impact of inter-user interference on performance incurred by random movement of a group of people wearing WBSNs. In this experiment, eight users (B-1 to B-8) walk randomly in the meeting room, each wearing one transmitter node (on left-arm) and one receiver node (at right waist). The experiment duration is 210 seconds, divided into seven steps as follows: (1) Step 1 (0-30 seconds): B-1 begins to transmit data and others keep silence, (2) Step 2 (30-60 seconds): B-2 wakes up and transmits data, (3) Step 3 (60-90 seconds): B-3 and B-4 wake up and begin to transmit data, (4) 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, (5) Step 5 (120-150 seconds): B-1 stops transmission, (6) Step 6 (150-180 seconds): B-1 and B-2 stop transmission, (7) Step 7 (180-210 seconds): B-1, 2, 3 and 4 stop transmission. The experiment stops at 210 seconds. The experimental results are shown in Fig.4.

In this experiment, when users walk randomly, we measure the PDR and throughput in each step as well as for the whole experiment, with both unslotted CSMA/CA and slotted CSMA/CA. The experimental results are shown in Fig. 4. According to the results, slotted CSMA/CA generally outperforms unslotted CSMA/CA in both PDR and throughput performance, indicating that slotted CSMA/CA is more robust to inter-user interference as compared to unslotted CSMA/CA.

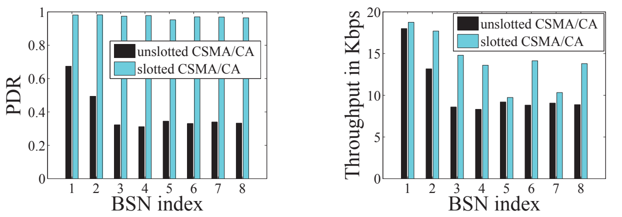
The performance results in Fig. 4 appear U shape patterns with regard to time. This implies that the severity of interference has direct impact on performance as the interference tends to be more severe in the middle steps of experiment as compared to the starting and ending steps.



(a) PDR of unslotted CSMA/CA (b) PDR of slotted CSMA/CA.



(c) Throughput of unslotted CSMA/CA. (d) Throughput of slotted CSMA/CA.



(e) Average PDR (f) Average Throughput

Fig. 4. Experimental results of random movement scenario.

From Figs. 4 (a) and (c), 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. 4 (d)). This may be 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.

We then measure the PDR and throughput performance for each user; the results are shown in Figs. 4 (e) and (f). 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 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. 1.

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. 4 (f)). The lower throughput of both B-5 and B-7 in slotted CSMA/CA, as compared to others (except B-1 and B-2), is caused by higher beacon loss ratio at those two nodes in the random movement.

As expected from our earlier results, the users can achieve stable PDR (at 95% level) in slotted CSMA/CA, regardless of the amount of competing users (see Figs. 4 (e)). Such a result further confirms that the slotted CSMA/CA is robust to inter-user interference in terms of PDR performance.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we investigated the impact of inter-user interference on WBSNs performance through extensive experiments. Our experimental results confirm the conclusions by existing simulation work on the adverse effect of inter-user interference on performance and the importance of inter-user interference mitigation on performance improvement. 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 the loss of beacons when interference is severe. Furthermore, we have some interesting findings on human-related impact factors such as body blockage, deployment orientation, and movement patterns, which have dramatic effects on the performance. We believe that our work can provide practical engineering insights and can be used as a reference for WBSN system design. The ongoing and future work includes designing effective protocols to mitigate inter-user interference for meeting the demands of realistic systems.

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