Performance Analysis of Coexisting IEEE 802.15.4-Based Health Monitoring WBANs

Mohammad Deylami and Emil Jovanov, *Senior Member, IEEE*

***Abstract*—Wireless Body Area Networks (WBANs) for health monitoring systems are required to meet stringent performance demands regarding the tradeoff between reliability, latency, and power efficiency. WBANs feature limited range and bandwidth and they are prone to interference. Considering the life-critical nature of some WBAN systems, we present an in-depth investigation of the situations where the dynamic coexistence of multiple WBANs may severely affect their performances. In this paper, we analytically study the effect of coexistence on the operation of WBANs. We present a mathematical analysis to precisely obtain the probabilities of successful communication and validate this analysis through simulation. Our simulation analysis indicates that in the default mode of operation, coexistence of three WBANs can lead to the loss of 20-85% of data transmissions for typical sensor configurations.**

I. INTRODUCTION

A Wireless Body Area Network (WBAN) is comprised of a number of sensors placed on a patient's body to monitor vital signs and transfer them to a processing server. power consumption is a critical design issues as some of the sensors are designed to be implanted inside the body and are supposed to work for years. Table 1 shows the characteristics of some of the highly used health monitoring sensors [1].

These sensors normally communicate using low-power wireless technologies like IEEE 802.15.4 [2]. Such standards may have different modes of operation from which the most power efficient ones shall be utilized. These modes incur issues regarding the coexistence of multiple WBANs. Coexistence situations, as depicted in Figure 1, are likely to happen in hospitals for patients and staff or for the elderly at nursing homes. As the WBANs share the wireless channels and transmission time, packet collisions are expected and this in turn would degrade the quality of health monitoring.

In this paper, we investigate the effect of dynamic coexistence on the performance of WBANs and present a precise mathematical analysis to model the situation. The paper is organized as follows: In section II, we review the relevant properties of the IEEE 802.15.4 standard and explain their relation to the coexistence situation. Section III reviews the related works. In section IV we analytically model the performance metrics of coexisting WBANs. Simulation results are presented in section V and Section VI concludes the paper with propositions for future work.

Table 1: Health monitoring sensors

Sensor	Sampling Rate (Hz)	Precision (bits)	Channels
EEG	125-1000	12-24	1-8
ECG	100-1000	12-24	1-3
Activity	25-100	12-24	3

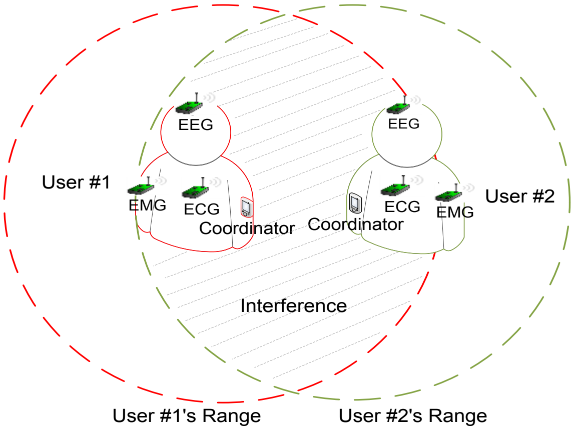

Figure 1: The coexistence situaton

II. COEXISTENCE OF IEEE 802.15.4-BASED WBANS

An IEEE 802.15.4 network is identified by a unique WPAN identifier set by its coordinator. The network may be configured in the star, mesh or cluster topologies. In the star topology, a number of sensors communicate directly with the coordinator which makes it the most effective choice for network maintenance and energy consumption. Most previously proposed WBAN structures use this topology.

With 250 Kbps data rate, the time required to transmit 4 bits is 16μsec which is called a *symbol* time. The coordinator divides the time into superframes delineated by beacons. The structure of the superframe is shown in Figure 2. The time interval between two consecutive beacons is called the *Beacon Interval* (*BI*) and the length of the active part is known as the *SuperframeDuration* (*SD*). *BI* and *SD* may be tuned to fit the traffic requirements based on the two parameters *macSuperframeOrder* (*SO*) and *macBeaconOrder* (*BO*). The corresponding relations are:

$$BI = aBaseSuperframeDuration * 2^{BO}$$

$$SD = aBaseSuperframeDuration * 2^{SO}$$

where $aBaseSuperframeDuration$ is 15.36 msec. The active part of the superframe is divided into 16 time slots. During the Contention Access Period (CAP) all devices may contend to access the channel using CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). During the Contention Free Period (CFP), Guaranteed Time Slots

This work was supported in part by the University of Alabama in Huntsville under Grant UAH 236338.

M. Deylami and E. Jovanov are with the Electrical and Engineering Department, University of Alabama in Huntsville, Huntsville, AL 35899 (E-mail: md0010@uah.edu and emil.jovanov@uah.edu).

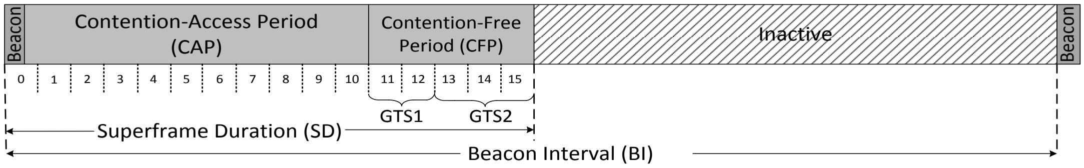

Figure 2: Superframe structure in IEEE 802.15.4

(GTSs) may be assigned to the sensors by the coordinator. The inherent nature of the CSMA/CA ameliorates the coexistence problem as the coexisting WBANs are able to share the channel and operate simultaneously. However, using GTSs eliminates CSMA/CA overheads such as backoffs and clear channel assessments which increase power consumption. Therefore using GTSs is widely accepted as the most power efficient approach for WBANs.

Coexistence shows its effect in two major forms: *beacon loss* and *data loss*. As carrier sensing is not used for beacon transmissions, beacons may easily collide with transmissions from coexisting WBANs. When a beacon is lost, the sensors lose synchronization and shall not transmit in the corresponding superframe. Since the standard does not provide coexistence mitigation methods, coexisting WBANs may suffer from significant performance degradation.

The effect of coexistence on data loss is related to the mode of operation. The criticality of the healthcare data may require the usage of acknowledgements and retransmissions. Yet the inflexible nature of the GTS mechanism as well as the lack of clear channel assessment and backoffs before the transmissions, make the acknowledgement mechanism inefficient at the time of coexistence. When two GTS periods overlap, data frames collide. A collided frame is retransmitted after *macAckWaitduration* (54 symbols) and this in turn results in more collisions. All the possible *aMaxFrameRetries* (3) retransmissions collide and the same collision pattern may repeat for the next frames until either the GTS ends or there are no more frames. In an extreme case, if the superframes of two identical WBANs overlap slightly such that the beacons are correctly received, all frames may collide and the power consumption of a sensor during a superframe may increase to *aMaxFrameRetries*+1 times with no successful data transmission. In practical environments where the necessary operational measures are taken such that external interferences from WLANs or other sources are not significant, coexistence would be a major source of interference. This makes the unacknowledged GTS mode the ideal case for the operation of WBANs.

IEEE 802.15.4 supports an orphaned device realignment mechanism that is performed after *aMaxLostBeacons* (4) successive beacon losses. However the beacon is not actually realigned as a realignment request from a sensor is replied with a *Coordinator Realignment* frame indicating the existence of the coordinator and not the timing of the beacon. The device is supposed to keep its receiver on to obtain the next coming beacon. If the beacon gets overlapped with data frames from another WBAN, the beacon will be lost for the whole duration of the coexistence. The sensor may even proceed with re-association to the coordinator which won't be effective as well. This situation may result in a total shutdown in the operation of a WBAN.

III. RELATED WORK

Several researches have exclusively focused on the problem of beacon collision. Since the IEEE 802.15.4 standard does not take beacon collision into account, some proposals have been discussed in Task Group 15.4b of IEEE 802 committee [3]. In the first one called the Time Division (TD) method; a coordinator sends its beacon during the inactive period of its neighboring coordinators. In the other proposal, the transmission of the beacon is done in a contention-free slot during a so-called Beacon Only Period (BOP), yet the method to choose that slot in a distributed fashion is not described.

Other works have proposed mechanisms to prevent or lower the harmful effects of coexistence. Power control mechanisms try to minimize interference by adapting the transmission power of sensors considering the dynamic situation of coexistence [4]. Another mechanism is to organize the active and inactive periods of the networks so that the active period of one overlaps with the inactive period of another [5]. There are also mechanisms where transmissions of WBANs are regulated by a centralized entity that oversees the whole environment [6]. For other wireless technologies like Bluetooth, methods have been developed to adjust the hopping sequence on the cleaner sub-channels [7][8].

IV. METHODS

We mathematically analyze the effects of coexistence on the operation of WBANs. For tractability, we assume the coexistence of homogeneous WBANs having the same number of sensors and data rates. Also as healthcare data is highly time-critical, we assume that at the time of a beacon loss, data is not buffered for the next superframe, since multiple beacon losses will cause unacceptable latency. Each WBAN contains N_S sensors and data frames contain the same length of payload. Sensor with index j transmits R_j frames per superframe. Table 2 shows the effective parameters in our modeling.

A. Probability of Successful Beacon Transmission

Assuming two coexisting WBANs, there are specific periods of time during a superframe that the beacon from one WBAN may collide with transmissions of the other. These periods are depicted in Figure 3 and the sum of them is defined as the duration of possible beacon collision (D_{BCL}):

$$D_{BCL} = 2 * T_{BCN} + \sum_{j=0}^{N_S} \left(R_j \times T_{FRM} + \left(R_j - 1\right) * LIFS + T_{BCN}\right) \qquad (1)$$

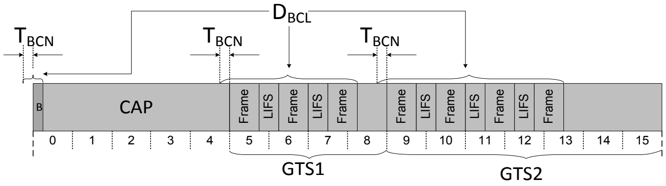

Figure 3: Durations of interest for beacon collision

Table 2: Effective parameters in transmissions

Parameter	Description	Value
LIFS	Inter-frame transmission Time	40 symbols
T_{FRM}	Duration of a frame transmission	238 symbols
T_{BCN}	Duration of a beacon transmission	40 symbols

The probability of beacon collision (P_{BCL}) would be:

$$P_{BCL} = D_{BCL}/BI \qquad (2)$$

In case of N_w coexisting WBANs, the coordinator of a WBAN may transmit its beacon successfully if it does not collide with the transmissions of $N_w - 1$ coexisting WBANs. The probability of a successful beacon transmission (P_{SBT}) in this case would be:

$$P_{SBT} = (1 - P_{BCL})^{N_w - 1} \qquad (3)$$

Yet we know that only a subset of the coexisting WBANs like N_{SBT} may successfully transmit the beacon and data frames. Therefore the formula has to be corrected to:

$$P_{SBT} = (1 - P_{BCL})^{N_{SBT} - 1} \qquad (4)$$

On the other hand, N_{SBT} is equal to the portion of the N_w WBANs that experience the chance of successful beacon transmission which means:

$$N_{SBT} = N_W * P_{SBT} = N_W * (1 - P_{BCL})^{N_{SBT} - 1} \qquad (5)$$

Equation (5) is in the form of $x = a * b^x$ also known as the *product algorithm* that is solved using the $Lambertw$ function [9]:

$$N_{SBT} = -Lambertw((N_W * ln(1 - P_{BCL})/(P_{BCL} - 1)/ln(1 - P_{BCL}) \qquad (6)$$

Knowing the number of transmitting WBANs, we may calculate the probability of successful data transmission. The first subtle issue that has to be taken into account is that a successful beacon transmission has implications on the data transmission of the coexisting WBANs. As the beacon has not collided with the transmissions of other WBANs, a time period equal to D_{BCL} has to be eliminated from the possible durations in which a coexisting WBAN may start transmitting. Then the candidate duration for successful data transmission (D_{SDT}) of each WBAN would be:

$$D_{SDT} = BI * (1 - P_{BCL})^{N_{SBT} - 1} \qquad (7)$$

Similar to (1), the duration of time that data transmitted from a sensor is suspected to collide with data transmission from a coexisting WBAN (D_{DCL}) would be:

$$D_{DCL} = \sum_{j=0}^{N_S} \left((R_j + 1) \times T_{FRM} + (R_j - 1) * LIFS \right) \qquad (8)$$

Considering two coexisting WBANs A and B, data transmissions from A would not collide with transmissions of B during a period of $D_{SDT} - 2 * D_{DCL}$ and during $2 * D_{DCL}$, half of data transmissions will collide on average. Therefore the probability of successful transmission (P^1_{SDT}) can be shown as:

$$P^1_{SDT} = (D_{SDT} - 2 * D_{DCL})/D_{SDT} * 1 + (2 * D_{DCL})/D_{SDT} * \frac{1}{2} = (D_{SDT} - D_{DCL})/D_{SDT} \qquad (9)$$

Finally, the probability of successful data transmission for each WBAN would be:

$$P_{SDT} = P_{SBT} * (P^1_{SDT})^{N_{SBT} - 1} \qquad (10)$$

V. RESULTS

We verify our mathematical analysis through OPNET simulations. We have developed a simulation model for the parallel operation of coexisting IEEE 802.15.4 based WBANs. We simulate the operation of WBANs in a dynamic situation with changing number of coexisting WBANs and with random time offset between the beacons. Our goal is to explore the design space by simulating typical practical scenarios. We set up homogeneous WBANs typical for monitoring of cardiac patients in hospitals. We define four types of WBANs (W1-W4) with different number of sensors, channels and sampling rates to cover different data rates. All samples are 16 bits. Each W1 includes 8 EEG channels sampling at 250 Hz, 1 ECG at 1000 Hz and 3 activity channels at 100 Hz. Each W2 includes 3 ECGs at 500 Hz and 6 activity channels at 100 Hz. Each W3 includes 1 EEG at 500 Hz and 3 activity channels at 100 Hz and each W4 has 1 ECG at 250 Hz and 3 activity channels at 50 Hz. The collective data rates are 52.8 Kbps, 33.6 Kbps, 12.8 Kbps and 6.4 Kbps respectively.

Considering the low required latency for cardiac monitoring, we set the common beacon interval to 0.983sec (*BO = 6*). Larger values of *BI* would result in slightly less chance for beacon collision as the overall beacon transmission time represents a smaller portion of the BI interval; smaller BIs increase the probability of collisions. In our simulations, we randomly place up to 100 WBANs in an area of 200m*200m with random movements and run the simulations for 100000 sec. The effective transmission range is set to 30m and collisions may happen if two nodes are in each other's ranges. At the end of the simulation we have the distribution of the coexisting WBANs as well as the received traffic at each coordinator plus the record of the reception of the beacons.

Figure 4 shows the comparison between the results from the simulation and theoretical analysis for successful beacon transmissions that can also be interpreted as the expected number of successfully transmitting WBANs. Two data rates corresponding to W1 and W3 are used. In Figure 5, the percentage of successfully transmitted data frames is shown for the four different system configurations previously described. As it is shown, the effect of coexistence is more severe with higher data rates.

We also simulate a system architecture where bursts of data are transmitted based on random or periodical events. Each user carries one ECG and one activity sensor. The ECG sends the timing of the heartbeat intervals (one to four 32bit timestamps per second). In addition, raw ECG signal is collected for one minute every one hour and also at the time of random events happening based on a Poisson distribution with the mean value of one hour. The activity sensor sends one 32 bit processed motion data on a regular basis every second. Raw data (3 channels at 100 Hz) for the last one minute is sent at the time of events randomly happening based on a Poisson distribution with the mean value of 15 minutes. Other parameters are the same as before. Figure 6 shows the percentage of successful data frame transmissions with these variable data rates. Although being based on fixed data rates, our theoretical model produces matching results by applying average data rates in the relations.

VI. CONCLUSIONS AND PROPOSITIONS

Dynamic coexistence of multiple WBANs may result in severe degradation in their performances. In this paper, we presented a theoretical analysis on the effect of coexistence on the probabilities of successful beacon and data transmission. We discussed why the inflexible nature of GTS transmissions has a low resilience against the effects of coexistence. In order to increase this resilience, it is necessary to add a mechanism to the IEEE 802.15.4 standard to resynchronize the sensors with the coordinator at the time of beacon loss so that the current superframe would not be wasted. We explained why the lack a mechanism to change the timing of the beacon transmission may result in a complete service shutdown for WBANs. Therefore we propose adding a mechanism to change the position of the beacon transmission in time whenever persistent interference takes place. The details of these propositions will be presented in the follow up papers.

ACKNOWLEDGMENT

We want to thank OPNET Technologies, Inc. for providing us with the simulation environment.

REFERENCES

[1] C. Otto, A. Milenkovic, and E. Jovanov, "System Architecture of a Wireless Body Area Sensor Network for Ubiquitous Health Monitoring," *Journal of Mobile Multimedia*, vol. 1, pp. 307-326, 2006.

[2] "IEEE Draft Standard for Local and metropolitan area networks - Part 15.4: Low-Rate Wireless Personal Area Networks (WPANs)." 2011.

[3] "T.G.15.4b, http://grouper.ieee.org/groups/802/15/pub/TG4b.html." .

[4] Gengfa Fang, E. Dutkiewicz, Kegen Yu, R. Vesilo, and Yiwei Yu, "Distributed Inter-Network Interference Coordination for Wireless Body Area Networks," presented at the IEEE Global Telecommunications Conference (GLOBECOM), 2010, pp. 1-5.

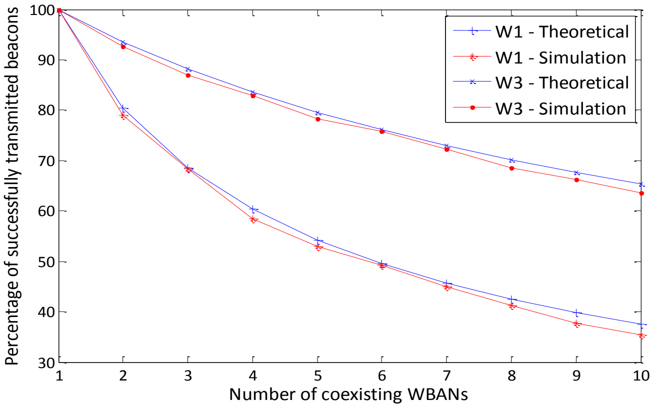

Figure 4: Comparison between the theoretical and simulation results for beacon transmission

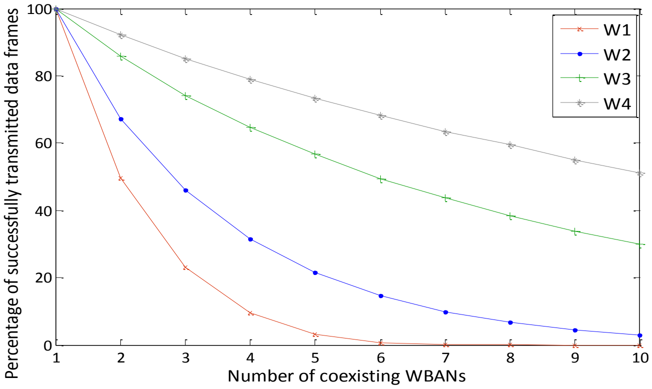

Figure 5: Effect of coexistence on fixed rate data transmission

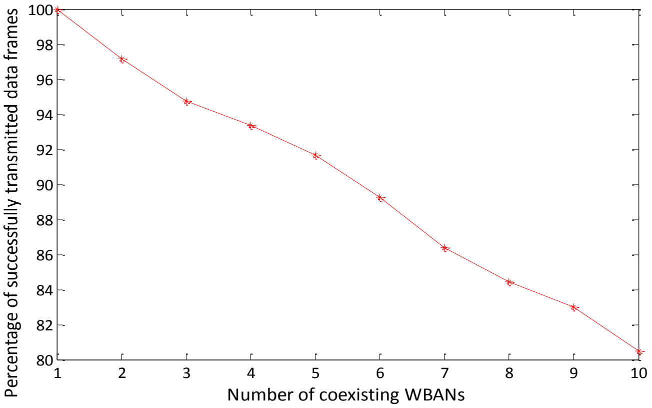

Figure 6: Effect of coexistence on bursty data transmission

[5] Tae Hyun Kim, Jae Yeol Ha, and Sunghyun Choi, "Improving Spectral and Temporal Efficiency of Collocated IEEE 802.15.4 LR-WPANs," *Mobile Computing, IEEE Transactions on*, vol. 8, no. 12, pp. 1596-1609, 2009.

[6] P. Ferrari, A. Flammini, D. Marioli, E. Sisinni, and A. Taroni, "Synchronized Wireless Sensor Networks for coexistence," presented at the IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), 2008, pp. 656-663.

[7] Jingli Li and Xiangqian Liu, "A Collision Resolution Technique for Robust Coexistence of Multiple Bluetooth Piconets," in *Vehicular Technology Conference, 2006. VTC-2006 Fall. 2006 IEEE 64th*, 2006, pp. 1-5.

[8] G. Pasolini, "Analytical investigation on the coexistence of Bluetooth piconets," *Communications Letters, IEEE*, vol. 8, no. 3, pp. 144-146, 2004.

[9] R. Corless and G. Gonnet, "On the Lambert W function," *Advances in Computational Mathematics*, pp. 329-359, 1996.