A Distributed Scheme to Manage The Dynamic Coexistence of IEEE 802.15.4-Based Health-Monitoring WBANs

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***Abstract*—The overlap of transmission ranges between wireless networks as a result of mobility is referred to as dynamic coexistence. The interference caused by coexistence may significantly affect the performance of wireless body area networks (WBANs) where reliability is particularly critical for health monitoring applications. In this paper, we analytically study the effects of dynamic coexistence on the operation of IEEE 802.15.4-based health monitoring WBANs. The current IEEE 802.15.4 standard lacks mechanisms for effectively managing the coexistence of mobile WBANs. Considering the specific characteristics and requirements of health monitoring WBANs, we propose the dynamic coexistence management (DCM) mechanism to make IEEE 802.15.4-based WBANs able to detect and mitigate the harmful effects of coexistence. We assess the effectiveness of this scheme using extensive OPNET simulations. Our results indicate that DCM improves the successful transmission rates of dynamically coexisting WBANs by 20%–25% for typical medical monitoring applications.**

***Index Terms*—Coexistence, health monitoring, IEEE 802.15.4, mobile, wireless body area network (WBAN).**

I. INTRODUCTION

A WIRELESS body area network (WBAN) is a type of sensor network typically aimed at the acquisition of health-related data [1]. Vital signs are collected using sensors that are placed on or implanted inside the body and transmit their data to a gateway, which can forward them to medical servers. Examples of the most common health monitoring sensors are activity sensors (accelerometers), electrocardiographs (ECGs) for monitoring heart activity, and electroencephalographs (EEGs) for monitoring brain electrical activity [2].

The overlap of ranges between wireless networks is referred to as *coexistence*, which can be classified as *static* coexistence (for nonmobile network nodes) and *dynamic* coexistence (for mobile nodes). WBANs are as mobile as their users; therefore, they may dynamically coexist with a varying number of other WBANs during their operation. For instance, dynamic coexistence may happen when a group of people gather in the dining hall at an assisted living home. The interference caused by the transmissions of coexisting WBANs can significantly affect their functionality, particularly in medical environments, where data availability is critical. Thus, the focus of this work is not increasing the efficiency of sensor networks in general; rather, it is providing reliability in the transmission of critical health monitoring data.

In this paper we study the effects of coexistence on the operation of IEEE 802.15.4-based health monitoring WBANs and propose a distributed mechanism to resolve the harmful effects of dynamic coexistence. The proposed scheme can be implemented as minimal amendments to the IEEE 802.15.4 standard. This paper is organized as follows. In Section II, we review the IEEE 802.15.4 standard and how it is incorporated by WBANs. Section III discusses the coexistence problem in general and reviews the related works. In Section IV, we study the effects of coexistence on the operation of IEEE 802.15.4-based WBANs. Section V presents an analytical model for the performance metrics of coexisting WBANs. In Section VI, we introduce a method for managing the dynamic coexistence of WBANs. Section VII presents the simulation setup and results, and Section IX concludes the paper.

II. IEEE 802.15.4-BASED WBANS

IEEE 802.15.4 [3] defines the Physical (PHY) and Medium Access (MAC) layers for low-rate wireless personal area networks (WPANs—a WBAN is a type of WPAN). IEEE 802.15.4 has been used in a wide range of applications including industrial automation, home control, and wireless sensor networking. Compared to standards such as IEEE 802.11 [4] and 802.15.1 [5], IEEE 802.15.4 offers lower complexity and power consumption that makes it suitable for WBANs with resource constrained devices. An IEEE 802.15.4-based WPAN may be configured in the star, mesh, or cluster topologies. In the star topology, a number of sensors communicate directly with a coordinator, which makes it the most effective choice regarding network maintenance overhead and energy consumption. The mesh and cluster topologies are mostly used in environmental and industrial monitoring applications covering large areas.

IEEE 802.15.4 uses direct sequence spread spectrum (DSSS) modulation with a default data rate of 250 kbps where each data *symbol* (4 bits) is coded into a 32-bit pseudo-noise (PN) code [3]. Transmissions, clear channel assessments (CCAs), and backoffs are aligned with units of time called *backoff periods* 320 μs each. The coordinator divides time into superframes by transmitting beacon frames. Each superframe includes an

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active part during which the nodes can communicate and an inactive part when the nodes may sleep and conserve energy. The time interval between two consecutive beacons is called a *beacon interval (BI)* and the length of the active part of the superframe is known as the *superframe duration (SD)*. *BI* and *SD* are adjusted using two parameters called *macSuperframeOrder (SO)* and *macBeaconOrder (BO)*.

The active part of the superframe includes 16 time slots divided between a contention access period (CAP) and an optional contention free period (CFP) during which guaranteed time slots (GTSs) can be assigned to the devices to transmit without contention. The channel access method in the CAP is carrier sense multiple access with collision avoidance (CSMA/CA) and time-division multiple access (TDMA) is used during the CFP. Since the CFP eliminates the need for CCAs and backoffs, it is widely accepted as the default mode of operation for WBANs.

III. COEXISTENCE PROBLEM AND RELATED WORK

As multiple wireless technologies use the 2.4 GHz industrial, scientific, and medical (ISM) frequency bands, there may be multiple sources of interference for a wireless transceiver at the same time. The coexistence problem can be classified in *heterogeneous* and *homogeneous* categories. *Heterogeneous* coexistence refers to the interference between different types of wireless technologies. Multiple methods for mitigating coexistence effects between IEEE 802.11 and IEEE 802.15.4 are reviewed in [6]. IEEE 802.15.4 defines sixteen channels in the 2.4 GHz band, but only four of them do not overlap with the default Wi-Fi channels (channels 1, 6, and 11 in North America).

On the other hand, coexistence of multiple transceivers of the same type shall be referred to as *homogeneous* coexistence, which may be addressed by either *centralized* or *distributed* methods. Ferrari *et al.* [7] proposed a centralized mechanism in which a resource allocator server receives requests from the WPAN coordinators and allocates transmission times to them. In distributed methods, networks can detect and manage the coexistence situation using *collaborative* or *noncollaborative* methods. Assigning nonoverlapping transmission channels based on graph coloring algorithms [8] and adapting the transmission power [9] are examples of these two categories, respectively. One solution that can be implemented as both a collaborative or a noncollaborative method is organizing the active and inactive periods of the coexisting WPANs such that the active period of each network overlaps with the inactive periods of the others. Based on this idea, Kim *et al.* [10] proposed a noncollaborative method where they assume that an IEEE 802.15.4-based WPAN is joining a group of preexisting networks and it selects its superframe timing based on the information carried in the beacons of the preexisting WPANs. This mechanism solves the problem of *static* (and not *dynamic*) coexistence since the mobility of WPANs is not considered and superframes are arranged only when WPANs are starting operation.

We proposed a distributed and collaborative scheme for managing the dynamic coexistence of health monitoring WBANs in medical environments in [11]. Using this method, when a coordinator detects harmful coexistence, it takes the role of a *coexistence manager*, and after exchanging requests and responses for collaboration, it finds the optimum arrangement for the superframes of the coexisting WBANs. The drawback of such a collaborative method is the complexity in maintaining synchronization after the superframe arrangement and the high overhead of the exchanged control messages. To the best of our knowledge, no method has previously been proposed to enable the WBANs to manage dynamic coexistence independently.

It should also be noted that if the length of the superframe of one WBAN is shorter than the active period of another, then the two superframes cannot be arranged without overlapping of the active periods. Also a coordinator has to suspend its operation for up to a maximum *BI* (251.65 s) in order to collect all possible beacons. In a shared environment like a hospital where all WBANs operate under the supervision of an authority, it is reasonable to use the same BIs for all WBANs. Therefore, a part of our proposition is that in order to achieve the highest resilience against interference, a unified BI should be used for all WBANs. We assume $BI = 0.98$ s ($BO = 6$) as the default value.

IV. EFFECTS OF COEXISTENCE ON WBANS

Dynamic coexistence affects the operation of IEEE 802.15.4-based WBANs in two major forms: *beacon collision* and *data collision*.

A. Beacon Collision

Since CCA is not used in beacon transmissions, beacons may easily collide with the transmissions of the coexisting WBANs. When a beacon is lost, the sensors cannot transmit in the corresponding superframe. Data frames may remain in the buffer for later superframes or be dropped based on the implementation and the buffer size. In the worst possible case, if the superframes of two WBANs have the same length and overlap such that the beacons collide, the operation of both WBANs will be suspended until they move out of each other's ranges.

IEEE 802.15.4 supports an orphan device realignment mechanism that is performed after 4 successive beacon losses. However, the beacon is not actually realigned since in response to a realignment request from a sensor, the coordinator sends a *coordinator realignment* frame that only indicates its presence and not the timing of the beacon. Several studies have exclusively focused on the problem of beacon loss. In this regard, two proposals (the time-division and the beacon-only-period methods) have been presented by Task Group 15.4b of the IEEE 802 committee [12], yet they remain in the form of abstract proposals with no implementation details. In [13], the authors propose scanning candidate channels by the coordinator during the inactive periods and switching to clean channels when beacons are lost. They assume that the "*the coordinator is connected to AC power*" which is an unrealistic assumption for wearable systems.

B. Data Collision

Collision of data frames has different consequences based on the acknowledged or unacknowledged modes of transmission. In the unacknowledged mode, collided frames are lost and not

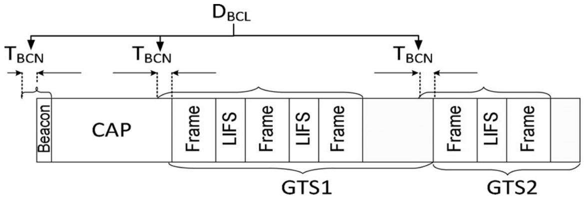

Fig. 1. Durations of possible beacon collision given two WBANs.

retransmitted. In the acknowledged mode, collided frames are retransmitted; however, lack of randomness in the timing of retransmissions, along with the absence of CCAs in CFP, can result in extreme inefficiency since the retransmitted frames may also collide. The coordinator can detect data loss in both modes by checking for missing frame sequence numbers.

V. Analytical Modeling of Coexistence

In order to provide an accurate and understandable analysis on the effects of coexistence on the operation of WBANs, we model the coexistence of homogeneous WBANs, i.e., WBANs with the same number of sensors and data rates. We consider the unacknowledged mode of transmission. Each WBAN contains N_S sensors, each data frame contains a maximum payload (114 bytes) and sensor j transmits R_j frames per superframe. The unit of time is *symbols* and all durations are defined relative to a superframe.

A. Probability of Successful Beacon Transmission

If the probability of successful beacon transmission is P_{SBT}, the beacon is lost and the frames remain in the buffer with the probability of $(1 - P_{SBT})$. Loss of beacons results in more frames to be transmitted in active superframes (when beacons are successfully transmitted); therefore, the expected value of the number of frames that sensor j needs to transmit during an active superframe is

$$N_F^j = \frac{R_j}{P_{SBT}}. \tag{1}$$

Transmission of a frame takes T_{FRM} (266 symbols, which is the sum of 114 bytes of payload and 19 bytes of header) and successive transmissions are separated by a long inter-frame spacing (LIFS) equal to 40 symbols. The duration of time that a sensor may occupy the channel (D_{CO}^j) is limited by its own GTS (GTS_j), that is

$$D_{CO}^j = \text{Min}\left(\text{GTS}_j, N_F^j * T_{FRM} + \left(N_F^j - 1\right) * \text{LIFS}\right). \tag{2}$$

Assuming two coexisting WBANs, there are specific periods of time that a beacon may collide with the transmissions of the other WBAN. These periods are depicted in Fig. 1 and the sum of them is the duration of possible beacon collision

$$D_{\mathrm{BCL}} = 2 * T_{\mathrm{BCN}} + \sum_{j=1}^{N_S} \left(D_{CO}^j + T_{\mathrm{BCN}}\right) \tag{3}$$

where T_{BCN} is a beacon transmission time (24 symbols). The probability of beacon collision in this case is

$$P_{\mathrm{BCL}} = \frac{D_{\mathrm{BCL}}}{BI}. \tag{4}$$

In the 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 where the no-collision events are independent. The probability of a successful beacon transmission is

$$P_{SBT} = \prod_{1}^{N_W - 1} (1 - P_{\mathrm{BCL}}) = (1 - P_{\mathrm{BCL}})^{N_W - 1}. \tag{5}$$

Yet only a subset of the $(N_W - 1)$ WBANs may have a successful beacon transmission and the transmission of data frames afterward. The expected number of these WBANs is

$$N_{SBT} = (N_W - 1) * P_{SBT}. \tag{6}$$

Therefore, we need to change (5) to

$$P_{SBT} = (1 - P_{\mathrm{BCL}})^{(N_W - 1) * P_{SBT}}. \tag{7}$$

It is important to notice that P_{SBT} shows itself on both sides of this equation and it is embedded in P_{BCL} (because of N_F^j) as well. To validate this analysis, we find numerical solutions to this equation and compare them with the simulation results in Section VII.

B. Probability of Successful Data Transmission

Unsuccessful beacon transmissions caused by collisions reduce data transmissions of sensors in their WBANs. Therefore, the possible duration of data transmission (D_{DT}) for each WBAN would be

$$D_{DT} = BI * (1 - P_{\mathrm{BCL}})^{N_{SBT}}. \tag{8}$$

Similar to (3), the duration of time that a data frame may collide with the data transmissions of a coexisting WBAN would be

$$D_{\mathrm{DCL}} = \sum_{j=1}^{N_S} \left(D_{CO}^j + T_{FRM}\right). \tag{9}$$

Considering two coexisting WBANs, W1 and W2, transmitted frames of W1 do not collide with the transmitted frames of W2 during a period of $D_{DT} - 2^* D_{\mathrm{DCL}}$ and during $2^* D_{\mathrm{DCL}}$, half of the frames collide on average. The probability of successful transmission with just one coexisting WBAN (P_{SDT1}) can be calculated as

$$\begin{aligned} P_{SDT1} &= \left(\frac{D_{DT} - 2 * D_{\mathrm{DCL}}}{D_{DT}}\right) * 1 + \left(\frac{2 * D_{\mathrm{DCL}}}{D_{DT}}\right) * \frac{1}{2} \\ &= \frac{D_{DT} - D_{\mathrm{DCL}}}{D_{DT}}. \end{aligned} \tag{10}$$

To know the probability of successful data transmission or equivalently the ratio of the successfully transmitted data frames to all generated data frames, we need to know the number of transmission trials per superframe. We know that for each successfully received beacon, N_F^j frames are put into the buffer, yet the number of them that actually get the chance for transmission during an active superframe (N_T^j) is limited by the length of the assigned GTS:

$$N_T^j = \mathrm{Min}\left(\frac{\mathrm{GTS}_j}{T_{FRM} + \mathrm{LIFS}}, N_F^j\right). \tag{11}$$

A data frame will be successfully transmitted if the beacon is received successfully, and it does not collide with the transmissions of the coexisting WBANs. The probability of successful transmission of the data frames for sensor j is

$$\begin{aligned} P_{SDT}^j &= \frac{\text{Successfully transmitted frames per super frame}}{\text{Generated frames per superframe}} \\ &= \frac{P_{SBT} * N_T^j * (P_{SDT1})^{N_{SBT}}}{R_j}. \end{aligned} \tag{12}$$

We may calculate an upper bound for the probability of successful data frame transmission by assuming that all beacons are received successfully. In this case, the duration of time that a sensor may occupy the channel is

$$D_{CO}^j = R_j * T_{FRM} + (R_j - 1) * \mathrm{LIFS}. \tag{13}$$

Similar to (9), the duration of time that a data frame may collide with the data frames of a coexisting WBAN is

$$D_{\mathrm{DCL}} = \sum_{j=1}^{N_S}\left(D_{CO}^j + T_{FRM}\right). \tag{14}$$

Considering two coexisting WBANs, W1 and W2, data frames of W1 do not collide with the transmissions of W2 with the probability of

$$P_{SDT1} = \frac{\mathrm{BI} - D_{\mathrm{DCL}}}{\mathrm{BI}}. \tag{15}$$

Then, the probability of successful data transmission, i.e., the probability that a transmitted data frame does not collide with the transmissions of the $N_W - 1$ coexisting WBANs, is

$$P_{SDT} = (P_{SDT1})^{N_W - 1}. \tag{16}$$

The validity of this equation will be assessed in the simulation results section. Table I lists the acronyms used in this analysis.

TABLE I
DEFINITION OF ACRONYMS AND VARIABLES

Acronym	Description
BI	Beacon Interval
$LIFS$	Long Inter-Frame Spacing (40 symbols)
T_{FRM}	Transmission time of a frame with maximum payload (266 symbols)
T_{BCN}	Transmission time of a beacon (24 symbols)
N_F^j	Expected number of frames that sensor j needs to transmit during an active superframe
D_{CO}^j	Duration of time that a sensor may occupy the channel
D_{BCL}	Duration of time that a beacon may collide with the transmissions of a coexisting WBAN
P_{BCL}	Probability of beacon collision with two coexisting WBANs
P_{SBT}	Probability of successful beacon transmission
N_{SBT}	Number of WBANs with successful beacon transmission
D_{DT}	Duration of time that data can be transmitted
D_{DCL}	Duration of time that a data frame may collide with the transmissions of a coexisting WBAN
P_{SDT1}	Probability of successful data transmission with two coexisting WBANs
N_T^j	Number of frames that sensor j can transmit during an active superframe
P_{SDT}^j	Probability of successful data transmission for sensor j
GTS_j	Length of the GTS assigned to sensor j

VI. DYNAMIC COEXISTENCE MANAGEMENT

We propose the dynamic coexistence management (DCM) mechanism to enable WBANs to manage the dynamic coexistence situation independently. Although the DCM mechanism is mainly targeted for health monitoring WBANs, it can be used in other types of IEEE 802.15.4-based networks as long as they use the same BIs. DCM uses *beacon replacement* and *channel switching* to resolve the beacon collision and the data collision respectively.

A. Beacon Replacement

At the end of the CFP, the coordinator can detect a beacon collision if it receives no data frames during that period. The beacon loss may be caused by a temporary interference or collision with the transmissions of a coexisting WBAN. Therefore, in DCM if a single beacon is lost, the coordinator will monitor the current working channel during the inactive part of the superframe. If no frames from coexisting WBANs are detected during this period, the coordinator will conclude that the beacon loss has been a one-time mishap and it will resume normal activity. However, if this loss recurs for a second consecutive superframe or frames from coexisting WBANs are detected, the coordinator will conclude that the beacon has to be replaced on the timeline to be received successfully by the sensors. The sensors are supposed to keep their transceivers on in case of consecutive beacon losses to be able to receive the replaced beacons.

When a beacon loss is detected, the coordinator will monitor the current channel for a BI. At the end of this search, the coordinator will have complete information about the coexisting WBANs. If the coordinator can find a gap with the minimum length of its own active period between the active durations of the coexisting WBANs, the coordinator will reschedule the transmission of its next beacon at the beginning of the gap. If a gap cannot be found, the coordinator will replace the beacon at the beginning of the largest available gap. Although this gap may not be sufficient for the whole active period, a successful beacon transmission will at least reestablish communication with the sensors in order to resume operation and inform them about a possible channel switch later on. Since the clocks are not synchronized between the coordinators and there may be other collisions shortly after the replacement, a guard time has to be used between the transmission of the replaced beacon and the beginning of the gap. We use a value of 10 ms in our simulations.

B. Channel Switching

Although changing the channel is the most trivial solution in order to avoid interference, it needs to be carefully investigated. At the end of a CFP, if the coordinator detects data loss, it has

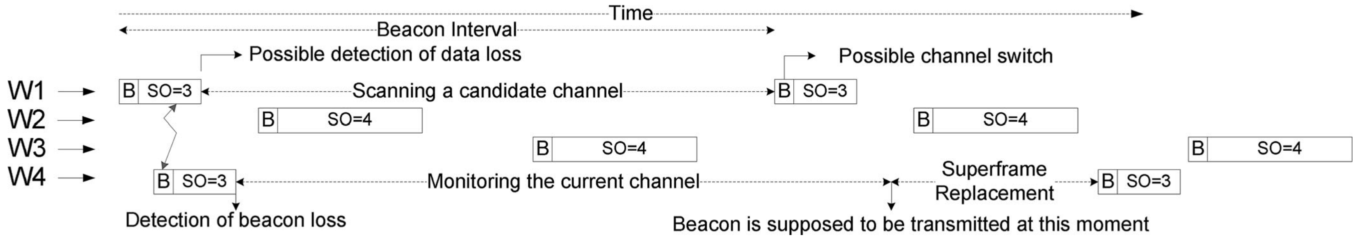

Fig. 2. Searching for a candidate channel and replacing the superframe in the DCM mechanism.

the chance to scan a candidate channel for a possible channel switch. The two possible options are: 1) *full BI scan*, and 2) *inactive period scan*. The benefit of the *full BI scan* is that the coordinator can collect the complete information about the preexisting WBANs in the candidate channel and the availability of a gap for its own active period. This benefit might come at the price of missed transmissions for one superframe since the beacon should not be transmitted during the scan. The advantage of the *inactive period scan* is the possibility of finding a gap without missing a beacon, even though the complete information about the preexisting WBANs in the candidate channel is not available. Also, if this scan is not successful, there is a chance that data loss will not persist in the next superframe and so no more actions will be needed.

In case of an unsuccessful search for a candidate channel, other channels will be monitored during the inactive parts of the next superframes. Altogether, the inactive period scan is more reasonable. If there is no inactive period (SD = BI), then the only choice will be to scan the candidate channel for a whole BI. If the coordinator does not receive any data frames during the CFP after the channel switch, it will conclude that the sensors have not received the last beacon and, therefore, they have not become aware of the channel switch. In this case the coordinator will switch back to the last working channel.

C. Implementation Issues

In case of a successful search for a candidate channel, the new channel and the offset to the beginning of the next superframe will be included in the next beacon. The time offset is defined as the number of *backoff periods* until the next beacon, which needs a 3-byte field added to the standard beacon frame (maximum BI = 251.65 s, which is equal to 786 432 backoff periods). The new channel will also need a 1-byte added field. DCM does not impose any computational overhead on the sensors since all DCM-related functionality, such as tracking the coexisting WBANs and scanning the candidate channels, are performed by the WBAN coordinators. However, DCM may force the sensors to keep their transceivers on for longer durations, which may increase their power consumption and will be described in the results section.

Fig. 2 illustrates the DCM mechanism. At the beginning, three WBANs (W1, W2, and W3) are coexisting with superframes that do not overlap. At some point in time, W4 enters the shared area with the preexisting WBANs and its beacon collides with the data transmissions of W1. At the end of W4's CFP, this WBAN will initiate current channel monitoring. Since it can detect data frames from W1, it continues the scan for a whole BI. At the end of this scan, it will have the complete information about the other three WBANs, and it can find the proper offset to replace its superframe. On the other hand, W1 will find data loss at the end of its own CFP, and it will search for a candidate channel during its inactive period. If the search is successful, it will inform its sensors about the channel switch using the next beacon. If a candidate channel is not found, it will not detect any more data loss due to the superframe replacement by W4 and there will not be a need for more actions.

VII. SIMULATION MODEL AND RESULTS

We simulate the operation of coexisting health monitoring WBANs using the OPNET simulation environment [14]. Our implementation includes

1) the IEEE 802.15.4 standard;
2) the interference and collision model;
3) the power consumption model; and
4) the DCM mechanism

A. Simulation Setup

We define four types of health monitoring WBANs (W1–W4) with typical numbers of sensors and sampling rates according to [2]. Activity, ECG, and EEG signals are collected using the operational parameters shown in Table II. All samples are 16 bits long and data frames are sent with the maximum payload. Each buffer size is set to 4 KB, which complies with the WBAN implementation in [1]. Power consumption parameters are set according to the CC2420 transceiver used in TelosB [15]. Three simulation scenarios are set up:

1) dynamic coexistence of homogeneous WBANs with fixed data rates in the unacknowledged mode;
2) dynamic coexistence of nonhomogeneous WBANs with and without the DCM mechanism; and
3) a real-world situation with a shared environment and coexisting WBANs

In the first scenario, the coexistence of homogeneous health monitoring WBANs is simulated to verify the analytical model. We randomly place 100 WBANs of the same type in a 200 m × 200 m shared area (typical of a large medical facility). Dynamic coexistence is simulated using the random waypoint mobility model [16]. Each WBAN selects a random destination, moves toward it with a random speed between 0.5 and 2 m/s (realistically low speeds for patients), waits for a random period (up to 60 s), and then selects another destination. The transmission ranges of the WBANs are set to 30 m (typical of indoor IEEE

TABLE II
SPECIFICATIONS OF THE SIMULATED WBANS

	Sensor type	Number of channels	Sampling frequency (Hz)	Collective data rate (kbps)	SO	GTS slots (Unacknowledged)	GTS slots (Acknowledged)
W1	EEG	8	250	52.8	5	6	7
	ECG	1	1000			3	4
	Activity	3	100			1	2
W2	ECG	3	500	28.8	4	9	10
	Activity	3	100			2	3
W3	EEG	1	500	12.8	3	6	7
	Activity	3	100			4	5
W4	ECG	1	250	6.4	2	7	8
	Activity	3	50			4	5

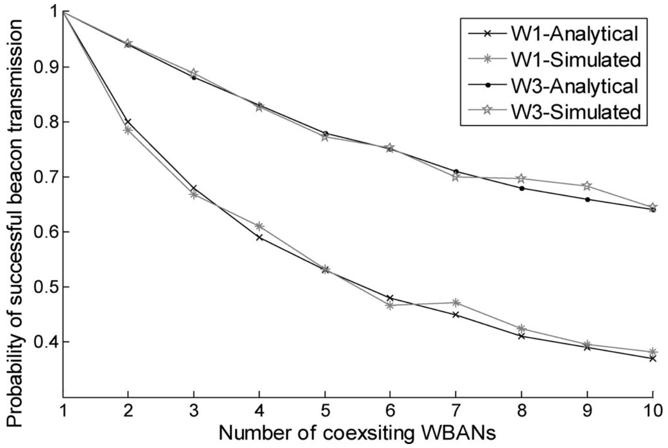

Fig. 3. Comparison between the analytical and simulated results for beacon loss.

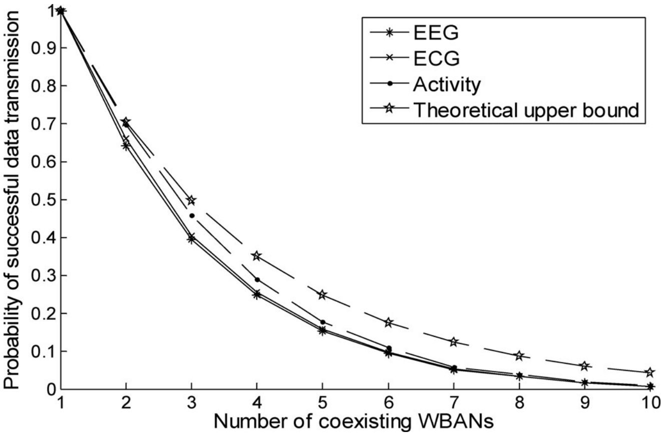

Fig. 4. Probability of successful data transmission for different sensors in a WBAN of the type W1.

802.15.4 ranges [10]) and all WBANs operate in the same channel. The simulation is run for 100 000 s. In the second scenario, 100 WBANs including 25 of each type (W1–W4) are placed in a 100 m × 100 m area with random movements similar to the previous scenario. The four nonoverlapping channels discussed in Section III are used. We consider the acknowledged and unacknowledged modes, each with and without DCM. The simulation is run for 100 000 s.

In the third scenario, we simulate 16 WBANs that start their operation with no coexistence in the acknowledged mode. The simulation continues for 100 s and then the WBANs randomly enter a simulated room during a course of 200 s. We measure the performance metrics of the WBANs with and without DCM and compare the results.

B. Results

Fig. 3 shows the comparison between the simulated and analytical results for the probability of successful beacon transmission obtained from (7). We show the results for two types of WBANs (W1 and W3). The other two configurations demonstrate the same matching results. Fig. 4 shows the analytical results for the probability of successful data transmission [see (12)] for the three sensors of a WBAN of type W1. This figure also includes the theoretical upper bound for the probability of successful data transmission [see (16)] for these sensors.

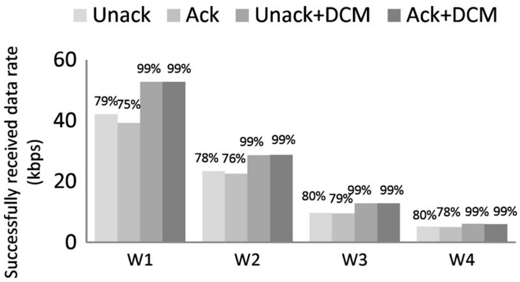

Fig. 5. Successfully received data rates in the four types of WBANs using different modes.

Figs. 5–8 present the results of the second scenario and the comparison between the measured parameters in four modes of operation. Unack and Ack refer to the unacknowledged and acknowledged modes of operation without DCM. Unack+DCM and Ack+DCM refer to the same modes with DCM support. The average number of coexisting WBANs for each WBAN during this simulation was measured as 4.55. Fig. 5 shows the successfully received data rates at the coordinators. As we expect, without DCM the acknowledged mode performs poorly at the time of coexistence. The successfully received data rates in this mode are even lower than those using the unacknowledged mode. Using DCM, both the acknowledged and unacknowledged modes show almost perfect transmission rates.

Fig. 6 shows the comparison between the power consumptions of the activity sensors in the four types of WBANs

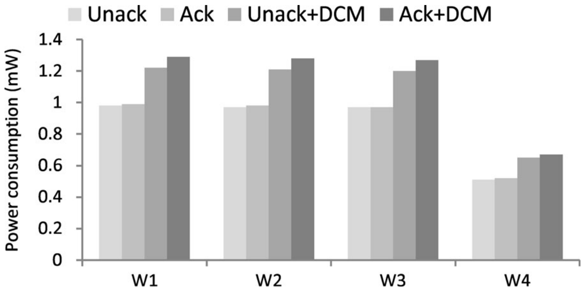

Fig. 6. Power consumption of the activity sensors in the four types of WBANs using different modes.

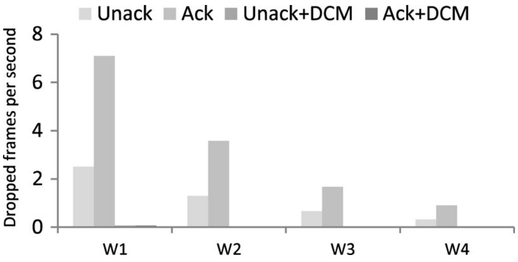

Fig. 7. Dropped frames per second in the four types of WBANs using different modes.

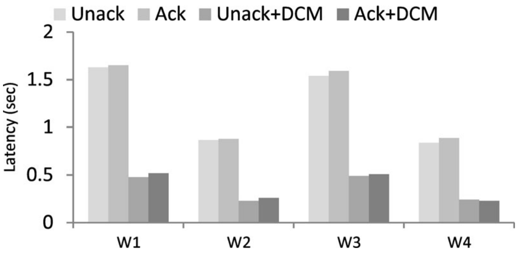

Fig. 8. Latency of the data frames sent by the activity sensors in the four types of WBANs using different modes.

using different modes. Higher power consumption is expected with DCM-enabled modes since the sensors have to keep their transceivers on for longer periods. However, the major part of this higher power consumption is due to the fact that when DCM is used, there are more successful beacon transmissions, which results in more active superframes and therefore more transmissions. So the higher power consumption in the DCM enabled modes is justified by the higher rate of successful transmissions.

Fig. 7 shows a very high rate of dropped frames in the acknowledged mode without DCM that is caused by buffer overflows. The unacknowledged mode without DCM has a lower rate of dropped frames, and with the DCM enabled modes, the rate of dropped frames is not noticeable. The latencies of the data frames transmitted by the activity sensors are compared in Fig. 8. Latency is defined as the period of time from the creation of a data frame until it is received by the coordinator. Without DCM, we observe higher latencies since the successfully transmitted frames may reach the destination after waiting in the buffer for later superframes. The DCM enabled modes show lower latencies since more frames get the chance to be transmitted without waiting for later superframes.

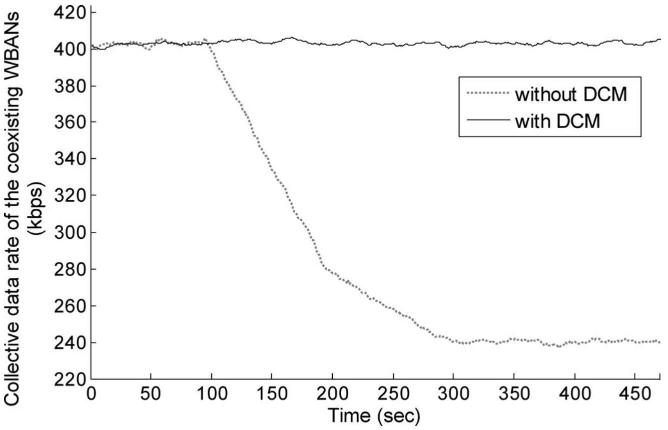

Fig. 9. Comparison between the collective data rate of all coexisting WBANs with and without DCM.

Fig. 9 shows the collective data rate for the 16 coexisting WBANs in the third scenario. Starting at 100 s when coexistence starts, without DCM the received data rates start to decrease consistently to almost 40% data loss. It should be noted that this performance degradation is not shared by the WBANs evenly since some of them face total service shutdown and there are others that do not lose much data. However, using DCM the set of the coexisting WBANs converges to a stable condition with no significant changes in the collective data rate. It is expected that some frames are lost as the WBANs enter each other's ranges; however, since the coordinators rearrange the active periods or find alternative communication channels, the losses can barely be observed in the collective data rate.

VIII. CONCLUSION

Dynamic coexistence of WBANs may result in the loss of critical health monitoring data. The criticality of such information in addition to the high probability of coexistence in healthcare environments necessitates the development of mechanisms that enable the WBANs to detect and mitigate the harmful effects of coexistence. In this paper, we introduced the DCM mechanism as an extension to the IEEE 802.15.4 standard which enables the WBANs to independently manage the coexistence situation in a distributed manner. We showed that the proposed mechanism can significantly improve the reliability of the WBANs in the dynamic coexistence situation. Future works include investigation of realistic patient mobility models and implementation of DCM on real-world WBANs.

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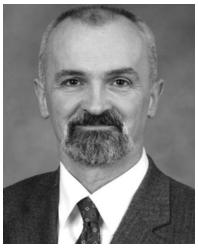

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