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RESEARCH ARTICLE

A novel method for mitigating the effects of dynamic coexistence on the operation of IEEE 802.15.4-based mobile WSNs

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ABSTRACT

Wireless networks dynamically coexist when their transmission ranges overlap as a result of mobility. Mobile wireless sensor networks (WSNs) may suffer from significant degradation of performance due to the interference caused by dynamic coexistence, which is particularly critical for health monitoring WSNs. In this paper, we propose a novel method to detect and mitigate the harmful effects of dynamic coexistence on the operation of IEEE 802.15.4-based mobile health monitoring WSNs. IEEE 802.15.4 uses the guaranteed time slots (GTS) mechanism to eliminate contention; however, successful transmissions cannot be guaranteed for coexisting WSNs. We show that using limited clear channel assessments at the beginning of the GTS enables the mobile WSNs to avoid collisions with minimum overhead. This method can also be used in combination with the previously proposed mechanisms for coexistence management. We analytically investigate the effects of using this method on the performance of the dynamically coexisting WSNs. We use OPNET simulation to investigate the coexistence of health monitoring WSNs and also to validate the proposed method. Our results indicate that using the proposed mechanism, 2–10 coexisting mobile WSNs with relatively high transmission rates (20–30% of maximum throughput) can achieve 20–90% higher rates of successful transmissions, with less than 10% increase in power consumption. Copyright © 2014 John Wiley & Sons, Ltd.

KEYWORDS
coexistence; IEEE 802.15.4; mobile wireless sensor networks; WSN; WPAN

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1. INTRODUCTION

Coexistence refers to the overlap of range between wireless networks, which may be *static* (for non-mobile network nodes) and *dynamic* (for mobile nodes). Because various wireless technologies such as IEEE 802.15.4 [1], IEEE 802.15.1 [2], and IEEE 802.11 [3] use the same 2.4-GHz Industrial, Scientific, and Medical bands, *heterogeneous* (different types) or *homogeneous* (the same type) devices are likely to coexist. Based on the different types of modulation and transmission powers, wireless transceivers may have different interference effects on each other.

In this paper, we study the effects of dynamic coexistence on the operation of homogeneous IEEE 802.15.4-based mobile wireless sensor networks (WSNs). We propose a new mechanism and compare it with the previously proposed methods for the detection and mitigation of the harmful effects of coexistence on the operation of IEEE 802.15.4-based networks. Some of these methods are designed to solve the static case of coexistence and others are suitable for specific applications. Therefore, there are coexistence situations where these methods are not effective. We intend to propose a method that can help with the detections of coexistence and avoiding collisions in more general situations with minimal assumptions about the target application.

Power constrained sensor systems usually take advantage of guaranteed time slots (GTS) to transmit without contention and the overheads of clear channel assessment (CCA). However, transmissions cannot be actually guaranteed when transmission time slots from coexisting networks overlap as a result of mobility. We investigate the benefits and costs of using CCAs at the beginning of GTS slots in order to avoid collisions and detect coexistence. This method can be added to the current IEEE 802.15.4 standard as a minimal optional feature. It can also be used in combination with the previously proposed mechanisms to provide a more effective management of coexisting situations.

This paper is organized as follows. Section 2 briefly introduces the IEEE 802.15.4 standard. Section 3 discusses the effects of coexistence on IEEE 802.15.4-based networks. In Section 4, existing methods for the detection of coexistence are reviewed. Section 5 reviews the exiting methods for managing the coexistence of IEEE 802.15.4-based networks. In Section 6, we introduce the CCA-enabled GTS method and analytically investigate its effects on transmissions. Section 7 presents the simulation setup and results and Section 8 concludes the paper.

2. IEEE 802.15.4-BASED NETWORKS

The IEEE 802.15.4 standard defines the physical and medium access (MAC) layers for wireless networks that are established for low-cost, low-power, and short-range applications. This technology has been used in a wide range of applications including WSNs, industrial automation, and appliance control. The ZigBee alliance [4] is responsible for the standardization of the protocol stacks and application profiles for this standard. Typical applications of this technology can be found in wireless personal area networks (WPANs) that interconnect devices around a person's workspace. An example would be health monitoring WPANs, which include sensors that collect vital signs and transmit them toward medical servers [5].

An IEEE 802.15.4-based network is established by a coordinator node, which may form a beacon-enabled or non-beacon-enabled network. In a non-beacon-enabled network, the nodes may randomly communicate with the coordinator, which forces the coordinator to be active at all times. This type of operation can be effective with unpredictable traffic patterns; however, it cannot be acceptable with power constrained coordinators and sensors with defined transmission rates, which is typical of health monitoring WPANs.

In a beacon-enabled network, time is divided into superframes delineated by beacons. The default data rate is 250 Kbps and each transmitted *symbol* is 4 bits. Transmissions, CCAs, and backoffs are aligned with time slots called the *backoff periods* (320 μs). Each superframe includes an 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* and *macBeaconOrder*, using the following relations:

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

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

where *aBaseSuperframeDuration* is equal to 48 backoff periods. The active part of the superframe includes a contention access period (CAP) and an optional contention free period (CFP) during which GTS slots can be assigned to the devices to transmit without contention. The channel access method in CAP is carrier sense multiple access with collision avoidance (CSMA/CA) and time division multiple access is used during CFP.

During CAP, each device keeps three variables for each transmission attempt: Number of Backoffs (NB), Contention Window (CW), and backoff exponent (BE). NB is initialized to 0 and counts the number of backoffs for the current transmission. CW is the number of backoff periods that the channel has to be free before a transmission can start. CW is set to 2 before each transmission attempts, which means two consecutive CCAs must succeed for each transmission. BE is the backoff exponent and is initialized to *macMinBE* (3). The backoff duration is uniformly chosen over $(0, 2^{\text{BE}} - 1)$ backoff periods. The backoff counter is decremented by 1 at each backoff period and it is frozen at the end of CAP. CCAs are done at the end of the backoff periods. If either of two CCAs fails, CW is reset to 2 and both NB and BE are incremented by one, provided that BE does not exceed *aMaxBE* (5). If the value of NB is greater than *macMaxCSMABackoff* (4), the CSMA/CA algorithm terminates with a channel access failure status.

The standard supports the acknowledged and unacknowledged modes of transmission. In the unacknowledged mode, after each transmission, a node waits for a long inter-frame spacing (LIFS is equal to 40 symbols) duration, after which it can proceed with transmissions of the next frame. In the acknowledged mode, the node should wait for at least a *macAckWaitDuration* (54 symbols) to receive an acknowledgement from the coordinator. If the acknowledgement is not received, the frame is retransmitted for at most for *aMaxFrameRetries* (3) times before being discarded.

3. EFFECTS OF COEXISTENCE ON IEEE 802.15.4-BASED NETWORKS

Coexistence may affect the operation of IEEE 802.15.4-based networks in two major forms: *beacon collision* and *data collision*.

3.1. Beacon collision

Because CCA is not used in beacon transmissions, beacons may easily collide with the transmissions of the coexisting networks. 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 implementation and buffer size. In the worst possible case, if the superframes of two networks have the same length and overlap such that the beacons collide, the operation of both networks will be suspended until they move out of each other's range.

3.2. 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 retransmitted. Using 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 an extreme inefficiency because the retransmitted frames may also collide. The coordinator can detect data loss in both modes by checking for missing frame sequence numbers.

4. METHODS FOR THE DETECTION OF COEXISTENCE

Coexistence is a special case of interference; therefore, there are more methods for detecting interference than methods for detecting coexistence. Interference detection methods can be classified as physical layer and MAC layer methods. The methods in the first category are based on physical layer parameters that are directly read from the chip registers. The second category is based on the receiving behavior of MAC frames. Based on the capabilities of the CC2420 transceivers that are used in TelosB [6] modules, we can use Received Signal Strength Index (RSSI), energy detection (ED), link quality indicator (LQI), and noise floor (*SSInoise*) in the physical layer. RSSI and ED are estimated values of the received signal power over a period of 8 symbols. Several studies [7,8] use RSSI and ED to detect the level of interference. LQI is a measure of chip error rate that is basically a scaled version of RSSI.

Detection of interference in the physical layer is relatively easy; however, it necessitates averaging over many samples, because instantaneous values of the samples do not have a direct relation to packet loss. Keeping an updated average for the level of interference, calculating the signal to noise ratio and checking the expected bit error rate from the standard tables needs a continuous monitoring of the channel, which can be a waste of energy. Hauer *et al.* [9] investigate the relation of RSSI and LQI to the interference from IEEE 802.11 devices. Their measurements show that RSSI is barely affected by the 802.11 traffic. In the same study, SSInoise (the values read from the RSSI register in CC2420) is also used to detect interference. Same as before, a single SSInoise value is unreliable in determining the presence of interference.

Detection of interference in layers above MAC is not a proper option because MAC retransmissions cannot be detected in higher layers. The most common method for detecting harmful interference at the MAC layer is packet loss [10,11]. Another method that can at least theoretically be used for the detection of coexistence is the usage of promiscuous mode by the coordinator. The coordinator can listen for beacons and packets from other networks; however, it may need to stay active even during the inactive period of the superframe and process many extra frames, which cannot be justified with low-rate transmissions and battery-operated coordinators.

5. EXISTING COEXISTENCE MANAGEMENT METHODS

In addition to the dynamic and static categorization, coexistence can be classified as heterogeneous and homogeneous. Heterogeneous coexistence refers to the interference between different types of wireless technologies. An example of this category that has been extensively studied is the coexistence between IEEE 802.11 and IEEE 802.15.4. The IEEE 802.15.4 standard defines 16 channels in the 2.4-GHz band and only four of them do not overlap with the default Wi-Fi channels (channels 1, 6, and 11 in North America). Angrisani *et al.* [12] show that up to 70% of IEEE 802.15.4 transmissions may be lost because of interference from IEEE 802.11-based transceivers. Guo *et al.* [13] measure the packet error rate of IEEE 802.15.4 under the interference from IEEE 802.11, IEEE 802.15.1, and microwave ovens. Kang *et al.* propose an adaptive interference aware algorithm using multiple channels in an IEEE 802.15.4-based WPAN in the presence of IEEE 802.11-based WLAN interference. The algorithm provides interference detection and avoidance by adaptively configuring multiple channels in an IEEE 802.15.4-based cluster-tree network. Multiple methods for mitigating coexistence effects between IEEE 802.11 and IEEE 802.15.4 are reviewed in [14].

Several wireless technologies take advantage of frequency hopping to counter interference. The combination of frequency hopping and cognitive radios [15] results in adaptive frequency hopping [16], which has been proved to be an effective technique to further extend the ability of frequency hopping to counter interference. WirelessHART [17] and ISA 100 [18] are wireless communication standards specifically designed for control applications in industrial environments and both are based on IEEE 802.15.4. WirelessHART uses channel hopping and combines it with time division multiple access to avoid interference and reduces multipath fading effects. ISA 100 implements adaptive channel hopping to use the channels with minimum interference. Although frequency hopping may help with resolving interference, more effective methods are still needed for the detection and mitigation of dynamic coexistence.

Coexistence of multiple transceivers of the same type is referred to as *homogeneous coexistence*. Methods for managing the coexistence of IEEE 802.15.4-based networks include *collaborative* or *non-collaborative* categories. In collaborative methods, coexisting networks may exchange information in order to reach an arrangement for their transmissions and in non-collaborative methods; they try to maximize their successful transmissions independently. CSMA/CA is the built-in mechanism that ameliorates the harmful effects of coexistence. Although it is designed to prevent collisions in a single network, it enables coexisting networks to share the channel and mitigates the interference caused by coexistence. However, this comes at the price of longer backoff periods and active durations for the transceivers, which increases power consumption and latency. In additions, the collective throughput declines as a result of contention when the number of coexisting networks increases. This will be investigated in more detail in the simulations section.

One method that can be implemented as both a collaborative or a non-collaborative method is organizing the active and inactive periods of the coexisting networks such that the active period of each network overlaps with the inactive periods of the others. Based on this idea, Kim *et al.* propose a non-collaborative method [19], where they assume that an IEEE 802.15.4-based WPAN is joining a group of pre-existing networks and it selects its superframe timing based on the information carried in the beacons of the pre-existing WPANs. This mechanism solves the problem of static (and not dynamic) coexistence because the mobility of WPANs is not considered and superframes are arranged only when WPANs are starting operation. In [20], the authors combine the idea of superframe arrangement with detecting received power levels and divide the coexisting WPANs into interfering and non-interfering WPANs. Considering the inaccuracy and constant fluctuations in the received power levels, this method has yet to be justified.

Collaborative methods are typically complex mechanisms with high additional overhead. In [21], a distributed and collaborative scheme for managing the dynamic coexistence of IEEE 802.15.4-based WPANs is proposed. It is shown that in order to reach a non-overlapping arrangement, the lengths of the superframes have to be limited to specific values. In addition, the method is suitable for environments with low dynamics of network topology, which is another limiting factor. Other issues include the complexity in maintaining synchronization after the superframe arrangement and the high overhead of the exchanged control messages. Overall, existing methods impose restricting assumptions on their target applications. Therefore, there is a need for simple and effective mechanisms that can be effective for coexisting IEEE 802.15.4-based WPANs with minimum assumptions.

6. COEXISTENCE MANAGEMENT USING CCA-ENABLED GUARANTEED TIME SLOTS

IEEE 802.15.4 provides the GTS mechanism to enable transmissions without collision and contention, which reduces the power consumption of the nodes as well. However, because the mobility of nodes may result in superframe overlaps, the transmissions in the CFP period cannot actually be guaranteed. On the other hand, CCA is a power consuming action that can verify the availability of the transmissions channel. In the simulation results section, we will show that using CCAs consistently, which is the key to the CSMA/CA mechanism, can significantly increase the power consumption of the nodes. However, CCAs can also be useful for networks that use GTS and are likely to experience coexistence. These networks can take advantage of CCAs in order to detect coexistence and avoid collisions.

Power constrained sensors typically buffer their samples, wake up at the beginning of their GTS, transmit, and go back to sleep. Therefore, a device can use CCAs at the beginning of its GTS in order to detect if a coexisting device is transmitting. Transmissions can be deferred until a coexisting device is done transmitting and be performed afterwards. Random backoffs are not used in this method, and when a node finds the channel free, it proceeds with its transmissions with no more CCAs. Considering the standard duration of 8 symbols for a CCA, two CCAs separated by an LIFS are needed in order to avoid a false detection of the free channel between successive transmissions. This mechanism can be added to the IEEE 802.15.4 standard as a minimal optional feature for situations where coexistence is expected. Using a simple flag in the data frames, the nodes can inform the coordinator about interference, which can be managed by an existing coexistence management mechanism, such as the collaborative superframe arrangement [21] or dynamic coexistence management mechanisms [22]. In the first mechanism, the coexisting coordinators collaborate to find an optimal arrangement for their superframes. One of the coexisting coordinators finds this arrangement and the other coordinators adjust their superframes accordingly. In the second mechanism, each coordinator independently tries to adjust its superframe in relation to the superframes of the coexisting WPANs to minimize the overlap.

Figure 1 illustrates an example of this mechanism. Node *B* in network *N2* is assigned a GTS that overlaps with the GTS of node *A* in network *N1*. At the beginning of its own GTS, *B* performs a CCA to make sure that the channel is free. However, it finds the channel busy; therefore, it suspends its transmission until the channel is found free. In the following, we will analytically investigate the costs of using this method in terms of the extra power consumption and delay that is imposed on the sensors. We consider the case of WSNs that use the tree topology. To make the mathematical analysis tractable, we make the following assumptions:

1. We will consider homogeneous networks, that is, networks with the same number of sensors and transmission rates, and the same BI.
2. Each sensor generates N_{GF} frames per superframe.
3. Each network includes a coordinator and N_S sensors.
4. The unacknowledged mode of transmission is considered.
5. Frames contain maximum payload (114 bytes).

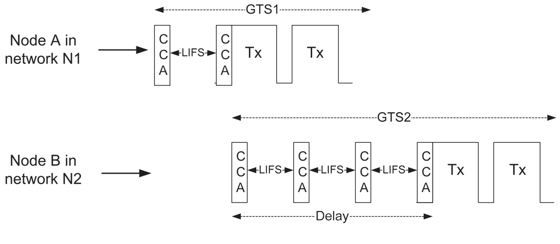

Figure 1. Using CCA-enabled GTS in order to avoid collisions.

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 a sensor needs to transmit during an active superframe is

$$N_{TF} = N_{GF}/P_{SBT} \tag{1}$$

Transmission of a frame takes T_{FRM} (266 symbols that is the sum of 114 bytes of payload and 19 bytes of header) and successive transmissions are separated by an LIFS. A *block of transmission* is defined as the duration of time that a sensor occupies the channel (transmits) during an active superframe. This value is bound by the length of the GTS that is assigned to a sensor (D_{GTS}) minus the delay caused by the CCAs (D_{CCA})

$$D_{CO} = Min\,(D_{GTS} - D_{CCA},\, N_{TF} * T_{FRM} + (N_{TF} - 1) * LIFS) \tag{2}$$

Assuming two coexisting networks, there are specific periods during a BI that a beacon may collide with the transmissions of the other network. These periods are depicted in Figure 2. The sum of these periods for N_S sensors is the duration of possible beacon collision (D_{BCL})

$$D_{BCL} = 2 * T_{BCN} + N_S \times (D_{CO} + T_{BCN}) \tag{3}$$

where T_{BCN} is a beacon transmission time (24 symbols). A beacon may collide with the transmissions of a coexisting network with the probability of

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

Assuming N_{CN} coexisting networks, a coordinator may transmit its beacon successfully if it does not collide with the transmissions of the active coexisting networks (the ones that have successful beacon transmissions). Then the probability of a successful beacon transmission would be

$$P_{SBT} = 1 - (N_{CN} - 1) \times P_{SBT} \times P_{BCL} \tag{5}$$

where the term $(N_{CN} - 1) \times P_{SBT}$ is the expected value of the active networks from $(N_{CN} - 1)$ coexisting networks. Equation (5) can be reduced to

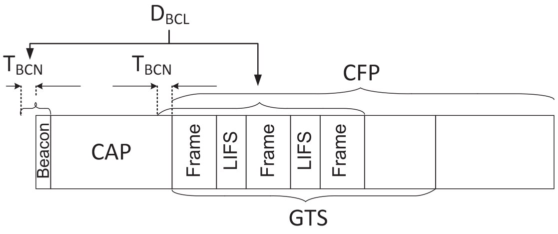

Figure 2. Durations of possible beacon collision with two WSNs each including a coordinator and a sensor.

$$P_{SBT} = \frac{1}{1 + (N_{CN} - 1) \times P_{BCL}} \tag{6}$$

The total number of active networks would be

$$N_{AN} = N_{CN} \times P_{SBT} \tag{7}$$

In order to find the imposed delay on the nodes, each block of transmission can be assumed as a seat and the timeline as a row of seats. When a sensor is about to transmit, it is as if a person is trying to take a seat. A person takes a seat if it is free or checks the next seat if it is taken. We need to find the number of seats that a person checks until he/she finds a free one. It should be mentioned that the trials are not independent because the number of pre-existing people (network) is known. Having found a taken seat, we need to subtract one from the number of candidates for taking the next seat; therefore, the probability of finding a free seat does not follow a geometric distribution.

Assuming S seats and P pre-existing people, PE_n is the probability of finding an empty seat in the nth trial, which is equal to the probability of finding the first n-1 seats occupied times the probability of finding the nth seat free

$$\begin{aligned} PE_n &= \prod_{i=1}^{n-1}\left(\frac{P-i+1}{S-i+1}\right) \times \left(\frac{(S-(n-1)) - (P-(n-1))}{S-(n-1)}\right) \\ &= \prod_{i=1}^{n-1}\left(\frac{P-i+1}{S-i+1}\right) \times \left(\frac{S-P}{S-n+1}\right) \end{aligned} \tag{8}$$

$$PE_1 = \frac{N_T - N_P}{N_T} \tag{9}$$

If SC is a random variable showing the number of seat checks until a free seat is found, the expected value of SC can be calculated as

$$E[SC] = PE_1 \times 1 + PE_2 \times 2 + \cdots + PE_P \times P = \sum_{i=1}^{P} PE_i \times i \tag{10}$$

Using this example, we can find the analytical solution to the problem of coexisting networks. The total number of available blocks of transmission in a superframe is

$$N_B = \frac{BI}{D_{CO}} \tag{11}$$

A factor that is different between the seat problem and the transmissions is the *contention* among the nodes that may be performing CCA at the same time. Because there is no coordination among the coexisting networks, multiple sensors from different networks, which we call contenders, may be performing CCAs at the same time.

Assuming i-1 unsuccessful CCA performed by a sensor, the expected value of contenders during the *i*-th CCA is

$$N_C^i = \frac{(N_{AN} - i + 1)}{N_B - i + 1} \times N_S \tag{12}$$

The probability of finding the channel free in the *i*-th CCA attempt is

$$P_W^i = \frac{1}{1 + N_C^i} \tag{13}$$

and the probability of finding the channel busy is

$$P_L^i = \frac{N_C^i}{1 + N_C^i} \tag{14}$$

The probability of finding the channel free after waiting for *n* blocks of transmission is the product of losing the CCA for the first *n*-1 times, times the probability of winning the *n*th CCA

$$P_F^n = \prod_{i=1}^{n-1} P_L^i \times P_W^n \tag{15}$$

If *B* is a random variable showing the number of blocks of transmission that a node needs to wait until the channel is found free, its expected value is

$$\begin{aligned} E[B] &= P_F^1 \times 0 + P_F^2 \times \frac{1}{2} + \cdots + P_F^{N_{AN}} \times \frac{(2N_{AN} - 1) \times 1}{2} \\ &= \sum_{i=2}^{N_{AN}} P_F^i \times \frac{(2i - 3)}{2} \times 1 \end{aligned} \tag{16}$$

The delay caused by the CCA mechanism would be

$$D_{CCA} = D_{CO} \times E[B] \tag{17}$$

Assuming the transmit current consumption of a transceiver as I_{TX} and receive (also CCA) the current as I_{RX}, the consumed energy of a node during an active superframe is

$$EN_A = (D_{CO} \times I_{TX} + D_{CCA} \times I_{RX} + T_{BCN} \times I_{RX}) \times V_S \tag{18}$$

where V_S is the supply voltage, which we assume 3V in our implementation. EN_A is for the active superframes, and during the inactive superframes, power consumption is only

$$EN_I = T_{BCN} \times I_{RX} \times V_S \tag{19}$$

Therefore, the average power consumption of a sensor is

$$EN = P_{SBT} \times EN_A + (1 - P_{SBT}) \times EN_I \tag{20}$$

We have a set of inter-related equations for which we find numerical solutions. It is important to mention that in the presented analysis, quantities are assumed to be equal to their expected values and we have not used a stochastic (Markovian) model to find the relation between variables. As the assumptions at the beginning of the analysis show, the target of this analysis is WSNs with a known number of sensors and fixed transmission rates. These assumptions enable us to use the mentioned simplifications, and the validity of this analysis will be verified in the next section. Table I lists the variables used in this analysis. It is important to notice that the efficiency of the CCA-enabled GTS mechanism depends on multiple parameters, one of the most effective ones being the length of the GTS slots. Assuming two identical coexisting networks each having one sensor such that the GTS slots overlap, one sensor will delay its transmissions until the channel is free. If the length of the slot is long enough so that there is enough time for performing the delayed transmissions in the same GTS slot, the packets will be transmitted with minimum delay at the price of increased power consumption. However, if the length of the GTS slot is assigned such that there is no time for delayed transmissions, the packets remain in the buffer for later superframes, thus resulting in increased latency, but without an increase in power consumption. In both cases, there will be more successful transmissions compared with the standard CFP mechanism, because collisions are avoided.

7. SIMULATION SETUP AND RESULTS

We use the OPNET simulation environment to simulate the operations of coexisting IEEE 802.15.4-based networks and the proposed mechanism. Our implementation includes the following:

1. The IEEE 802.15.4 standard
2. The interference and collision model
3. The power consumption model
4. The CCA-enabled GTS mechanism

In this section, we discuss the simulation setup and results.

7.1. Simulation setup

In the first scenario, we compare the maximum throughput of IEEE 802.15.4 in CAP and CFP modes, in the acknowledged and unacknowledged modes of transmission. We simulate the operation of one network with different numbers of nodes in the star topology. $BO = 6$ s has been used in this simulation. The nodes send as many frames as they can with maximum payload.

Next, we need to justify the effectiveness of the proposed CCA-enabled GTS mechanism as well as the accuracy of the analytical model. In order to simulate a realistic scenario that involves mobility and variable number of

Table I. Definition of variables.

Variable	Description
B_I	I beacon interval
$LIFS$	LIFS long inter-frame spacing (40 symbols)
N_S	Number of sensors in a network
N_{CN}	Number of coexisting WPANs
T_{FRM}	Transmission time of a frame with maximum payload (266 symbols)
T_{BCN}	Transmission time of a beacon (24 symbols)
N_{GF}	Number of generated frames in a superframe
N_{TF}	Expected number of frames to be transmitted during an active superframe
D_{CO}	Duration of time that a sensor may occupy the channel
P_{SBT}	Duration of time that a beacon may collide with the transmissions of a coexisting network
D_{BCL}	Probability of beacon collision with two coexisting networks
P_{BCL}	Probability of successful beacon transmission
N_{AN}	Number of active networks (networks with successful beacon transmission)
N_B	Number of available blocks of transmission in a superframe
N_C^i	Expected value of contenders during the i'th CCA
P_W^i	Probability of winning a CCA with N_C^i contenders
P_L^i	Probability of losing the CCA with N_C^i contenders
P_F^n	Probability of finding the channel free after waiting for n blocks of transmission
D_{CCA}	Delay caused by the CCA mechanism
D_{GTS}	Length of the GTS that is assigned to a sensor
E_{N_A}	Consumed energy of a node during an active superframe
E_{N_I}	Consumed energy of a node during an inactive superframe
EN	Average consumed energy of a node

LIFS, long inter-frame spacing; WPAN, wireless personal area network; CCA, clear channel assessment; GTS, guaranteed time slots.

coexisting networks, we model the operation health monitoring WPANs. We define two types of sensors to be used in our simulations: an electrocardiograph sensor (ECG for monitoring heart activity) and an electroencephalograph sensor (EEG for monitoring brain activity), each with 1000-Hz sampling rate. Considering 16 bit samples, each sensor would generate a 16-Kbps data stream and the sensors may be applied with multiple channels.

The goal of our simulations is to put the WPANs in coexisting situations with different numbers of other WPANs. In a realistic scenario, these WPANs spend long durations without coexistence and during limited periods, they are exposed to coexistence. An example is the case of WPANs for health monitoring in assisted living facilities, where dynamic coexistence happens when patients gather in a dining hall. In order to study the coexisting situation, we need to consider a large number of coexisting WPANs in different scenarios. Therefore, instead of real mobility models, we use random mobility to put the WPANs in frequent and dynamic coexisting situations.

Dynamic coexistence is simulated using the random waypoint mobility model [23]. Each WPAN selects a random destination, moves toward it with a random speed between 0.5 and 2 m/s, waits for a random period (up to 60 s), and then selects another destination. We randomly place 100 WPANs of the same type in a 200 m by 200 m shared area and all WPANs operate in the same channel. The WPANs start their operation at a random moment and there is no synchronization or alignment assumed between the starting times of the WPANs. The transmission range of

Table II. Maximum data rates in CAP and CFP.

Mode	Number of nodes	Maximum data rate (Kbps)	
		Unacknowledged mode	Acknowledged mode
CFP	1	160	135
CFP	2	160	135
CFP	3	159	134
CFP	4	158	133
CAP	1	130	128
CAP	2	116	114
CAP	3	110	107
CAP	4	102	100

CAP, contention access period; CFP, contention free period.

the WPANs is set to 30 m (typical of indoor IEEE 802.15.4 ranges [19]) and all WPANs operate in the same channel. Power consumption parameters are set according to the CC2420 transceiver used in TelosB [6]. The simulations are run for 100 000 s.

In the second scenario, we investigate the accuracy of the analytical model with different values of *BO*. Each WPAN includes one ECG and one EEG sensor, resulting in a 32-Kbps data stream and each sensor has three GTS slots in the CFP mode. We increase the value of BO from 2 to 9 and the value of *SO* increases from 1 to 8, correspondingly. We measure the power consumption of the sensors and compare them to the value obtained from (20). We define the error of our analytical model as

$$Err = \frac{|EN_{ANL} - EN_{SIM}|}{EN_{SIM}} \times 100$$

where EN_{ANL} and EN_{SIM} are the consumed energy values obtained from the analytical model and the simulation, respectively. In the third scenario, we compare the performance of CFP, CCA-enabled CFP, and CAP in the coexistence situation. The values of BO and SO are set to 6 and 5, respectively. Each WPAN includes one ECG and one EEG sensor, and each sensor has three GTS slots in the CFP mode. Each of the CFP, CCA-enabled CFP, and CAP modes is simulated with and without acknowledgements.

In the fourth scenario, we intend to show the effect of using different numbers of sensors in each WPAN. We increase the number of sensors in each WPAN from 1 to 5 and show the performance of different modes with a fixed value of coexisting WPANs, which is set to 5. The values of BO and SO are set to 6 and 5 and we measure the error in the calculation of power consumption, similar to the second scenario.

7.2. Results

Table II shows the results of the first simulated scenario. It should be mentioned that as a result of the slotted CSMA/CA mechanism, if two nodes perform their CCA at the same backoff slot, their packets collide [24], which explain the decreasing successful data rates with increasing number of nodes. As it is expected and the simulations confirm, CFP provides a higher maximum data rate that does not change significantly with increased number of nodes, because there is no contention in accessing the channel. With more nodes in the CAP mode, there is more contention, latency, and chance of collision, and as a result, less maximum data rates.

Figure 3 shows the error rates for different values of BO and coexisting WPANs. It can be observed that with larger values of BO, the analytical model is more accurate. This comes from the fact that with smaller values of BO, there are more beacons being transmitted and with more beacons, the small errors in the calculation of P_{SBT} accumulate in the value of the consumed power.

Figure 4 shows the successfully received traffic rates in three unacknowledged modes with increasing number of WPANs. As we expect, CAP results in higher rates of successfully transmitted frames compared with CFP. This is achieved by sharing the channel with the coexisting WPANs, which comes at the price of higher power consumption. The CCA-enabled mode achieves higher traffic rates compared with both other modes with low number of coexisting WPANs ($\leq$ 3), and with higher numbers of coexisting WPANs, CCA-enabled CFP performs almost equal to CAP. The CCA-enabled mode achieves around 20% higher data rates compared with CFP for 2–4 coexisting WPANs, which increases to almost 60% higher data rates for higher number of coexisting WPANs (8–10).

Figure 5 shows the comparison between the power consumption of the sensors. For the CAP mode, it is observed that the consumed power increases with the increasing number of coexisting WPANs until it reaches a peak and then it declines. The reason is that up to a certain number of coexisting WPANs, each sensor will spend more time doing CCAs and backoffs, but finally, it succeeds with the transmission of its buffered frames. However, after

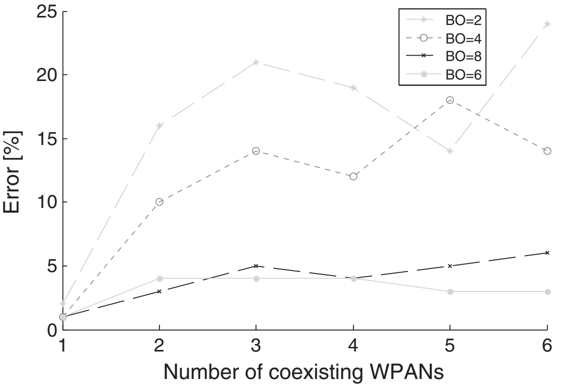

Figure 3. Power consumption error as a function of BO and the number of coexisting WPANs.

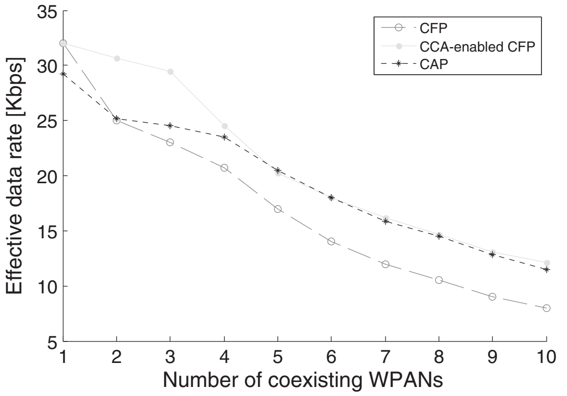

Figure 4. Comparison between the successfully received traffic in CFP, CCA-enabled CFP, and CAP modes without acknowledgements.

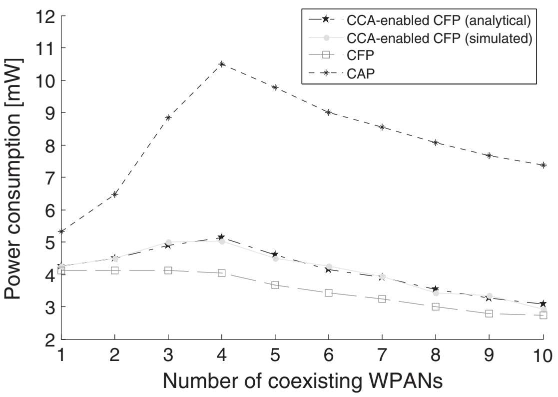

Figure 5. Comparison between the power consumption of the sensors in CFP, CCA-enabled CFP, and CAP modes without acknowledgements.

that point, the probability of successful beacon transmission is so low that the frames do not get the chance for transmission and that explains the decreasing power consumption. The frames may remain in the buffer and finally get dropped as a result of overflow.

The same pattern for power consumption can be observed with the CCA-enabled mode but with much smaller values. The maximum power consumption overhead of the CCA-enabled mode compared with the CFP mode is 20% for four coexisting WPANs. As the figure shows, the analytical model produces matching results with the simulations. The analytical results are obtained using Equation (20). In the CFP mode, the power consumption stays flat until a certain point and then it decreases. The reason is that up to that point, the frames are eventually transmitted after staying in the buffer and without additional overheads such as CCA. After that point, the power consumption decreases for the same reason as the previous modes.

Figure 6 shows the successfully received traffic rates in the acknowledged modes. It can be observed that the CCA-enabled CFP mode achieves very close rates compared with the CAP mode and higher rates compared with the CFP mode. The acknowledged CCA-enabled mode achieves around 20% higher data rates compared with the acknowledged CFP for 2–4 coexisting WPANs, which increases to almost 90% higher data rates for higher number of coexisting WPANs (8–10).

Figure 7 shows the power consumption of the sensors, with peaking values that happen with lower number of coexisting WPANs, compared with the unacknowledged mode. Acknowledgment frame transmissions and frame retransmissions keep the channel busy for longer periods compared with the acknowledged mode, which results in lower probabilities of successful beacon transmission with fewer coexisting WPANs. The higher successfully transmitted traffic rates using the acknowledged CCA-enabled CFP compared with the CFP come at a price of a minimum increases in power consumption ($\leq = 10\%$).

Figure 8 shows the results from the fourth scenario as the successfully received data rate per sensor. The pattern

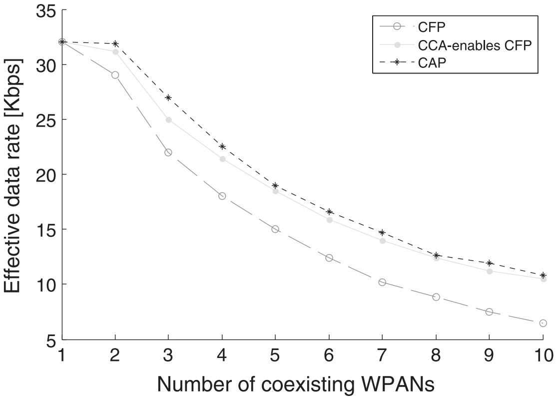

Figure 6. Comparison between the successfully received traffic in CFP, CCA-enabled CFP, and CAP modes with acknowledgements.

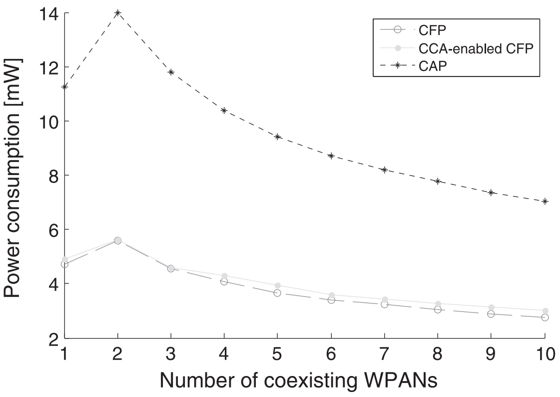

Figure 7. Comparison between the power consumption of the sensors in CFP, CCA-enabled CFP, and CAP modes with acknowledgements.

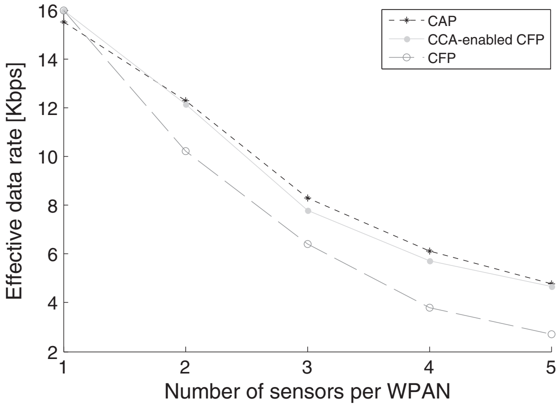

Figure 8. Comparison between the successfully received data rates in CFP, CCA-enabled CFP, and CAP with different numbers of sensors per WPAN.

of results is similar to Figure 4 with the CCA-enabled CFP mode performing close to the CAP mode and with less power consumption. The error rates in the computation of the power consumption are less than 5%, which proves the accuracy of the analytical model for a variable number of nodes.

8. CONCLUSION

The interference caused by the dynamic coexistence of IEEE 802.15.4-based mobile WSNs can significantly affect their performance. The IEEE standard lacks mechanisms for detecting and managing the dynamic coexistence situation and the previously proposed mechanisms are specific to particular applications. Therefore, new solutions can be effective for a wider range of IEEE 802.15.4-based networks. In this paper, we proposed the use of CCA at the beginning of GTS in order to avoid collisions that are caused by mobility and detect coexistence. We investigated the trade-off between the higher rates of successful transmissions and the higher power consumptions as a result of using this method. The simulation results show that the proposed mechanism can significantly reduce collisions and improve the performance of coexisting networks, with minimum increase in the power consumption of the mobile nodes.

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