# Time-Domain Cooperative Coexistence of BLE and IEEE 802.15.4 Networks

Onur Carhacioglu*†, Pouria Zand†, Majid Nabi*
*Department of Electrical Engineering, Eindhoven University of Technology, Eindhoven, the Netherlands
†Holst Centre / IMEC-NL, High Tech Campus 31, 5656 AE Eindhoven, The Netherlands
Email: O.carhacioglu@tue.nl, Pouria.Zand@imec-nl.nl, m.nabi@tue.nl

***Abstract*—Wireless sensor networks have entered into our lives, and are expected to be even more widespread in the near future. Bluetooth Low Energy (BLE) and IEEE 802.15.4 are two low-power wireless standards that are widely used in sensor network applications. They share the same unlicensed 2.4 GHz ISM spectrum. To be able to employ both technologies in the same environment in a heterogeneous network, the creation of a proper coexistence mechanism is imperative. In this paper, we propose and develop a cooperative mechanism for the coexistence of co-located IEEE 802.15.4 and BLE networks in the time domain. This mechanism tries to avoid overlap of communications in these networks in order to decrease the chance of Cross-Technology Interference (CTI) and thus packet drops. The proposed mechanism does not impose any protocol change. The performance of the proposed mechanism is evaluated by using real hardware devices. The experimental results show that the overall packet reception ratio improves up to 12%.**

***Keywords*—Cooperative Coexistence, BLE, Bluetooth Low Energy, IEEE 802.15.4, Wireless Sensor Networks**

## I. Introduction

With the emergence of the Internet-of-Things (IoT), the number of wireless devices has significantly increased. Two of the most popular wireless communication standards for IoT are BLE [1] and IEEE 802.15.4 [2]. In addition to the single operation of each of these standards, some applications require inter-operation of them in a heterogeneous network. However, inter-operation of these co-located technologies leads to CTI, because both of these standards operate in the 2.4 GHz unlicensed frequency band [3].

The MAC layers of these standards are responsible for scheduling the transmissions. However, simultaneous transmissions by devices in different technologies can still cause CTI, which affects the communication quality of both networks. While MAC layer mechanisms, such as CSMA and channel hopping, can slightly improve the communication reliability under CTI, they fail to provide highly reliable connections. The detrimental effect of CTI is even worse when there are other wireless transmissions in the same 2.4 GHz band by other standards, such as WiFi. The channel frequencies of BLE, IEEE 802.15.4 and WiFi are shown in Fig. 1. In order to cope with the CTI issue and improve the communication reliability, a coexistence method between various technologies that share the same spectrum is of foremost importance.



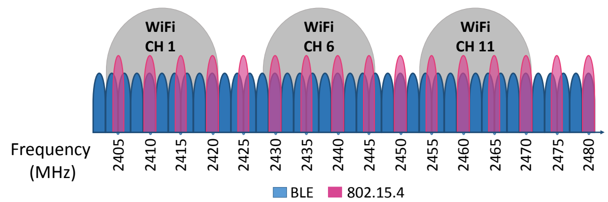



Fig. 1. Channels of BLE, IEEE 802.15.4, and WiFi in 2.4 GHz

A coexistence solution requires one radio to monitor the transmission of the other radios and schedule its transmission. The monitoring can be applied using cooperation [4], in which the radios share their transmission state with each other, or without cooperation [5], in which the radios try to sense the radio activities of each other. The non-cooperative approach attempts to predict the transmissions of the other radios using the previous measurements. However, this mechanism may not be able to precisely predict changes in the communication pattern of the other radios. Therefore, a cooperative approach is expected to provide more reliable data about the transmission state of the other radio. However, a cooperative approach requires a wireless device that integrates both wireless technologies and time synchronization between these technologies.

The frequency domain coexistence between BLE and IEEE 802.15.4 can be implemented by smart selection of transmission channels [6]. BLE uses 40 and IEEE 802.15.4 uses 16 frequency channels. Disjoint channels can be assigned to each technology with the cost of decreasing the number of available channels, which can be already scarce under other type of external interference, such as WiFi. A time-domain coexistence between BLE and IEEE 802.15.4 can be implemented by taking advantage of duty cycles that exist in both technologies with periodic active and inactive time periods. A time domain coexistence approach can be used as a standalone solution or a complementary solution to a frequency-domain coexistence.

In this paper, two time-domain cooperative algorithms are proposed for coexistence of connection-oriented BLE and beacon-enabled IEEE 802.15.4 networks. The algorithms use MAC layer APIs that are defined by the standards. Thus, the algorithms are non-intrusive and do not impose any changes in the standards. In one mechanism, the BLE network schedules its communications in such a way that it avoids interfering with the IEEE 802.15.4 network. In the other proposed solution, the IEEE 802.15.4 adapts itself to avoid collision with the BLE network. Both of the proposed solutions are implemented on real hardware devices and their performance is evaluated with respect to several metrics.

The paper is organized as follows. Section II will discuss the related work on the coexistence of various wireless technologies. Section III offers the necessary background knowledge about the standards. The proposed coexistence mechanisms are presented in Section IV. Section V describes the experimental setup and the achieved results. Section VI presents our conclusions.

## II. Related Work

Most of the existing literature about coexistence in 2.4 GHz transmissions focuses on WiFi interference. However, the effect of interference and how to mitigate it between BLE and IEEE 802.15.4 stays understudied.

The authors in [7] provide experimental tests in order to emphasize the interference problem between BLE, 802.15.4 and WiFi. Silva et.al. conclude that the BLE channel hopping performs good against interference. However, this study is limited to the PHY layer analysis. Also, this study does not provide any coexistence mechanism. In [3], another PHY layer interference analysis of Wifi, BLE, and IEEE 802.15.4 is conducted, but it is further extended for the MAC layers of these technologies. It is concluded that BLE is affected from the IEEE 802.15.4 interference more than the vice verca. Also, compared to IEEE 802.15.4, BLE is more resilient to WiFi interference. Furthermore, this study includes the effect of interference as the channel separation increases. If BLE and IEEE 802.15.4 channels are separated by 5MHz or more from each other, they do not interfere at all. However, WiFi interference affects the other transmissions, unless its channel is separated by more than 10 MHz from the channel being used by the affected network. Both [3] and [7] point out the interference problem, however they fail to provide any coexistence solution.

In [6], a frequency-domain cooperative coexistence solution is proposed for smart grid home area networks. The frequency domain scheduling is implemented by choosing BLE and IEEE 802.15.4 channels statically. Another frequency-domain coexistence mechanism is proposed in [8], in which authors explain the interference problem between IEEE 802.15.4, BLE and Bluetooth classic. They propose a cognitive radio mechanism which involves activating and deactivating channels. However, both [6] and [8] do not consider adjacent channel interference that is the main drawback of the frequency domain solutions. The low-cost wireless transceivers in the market do not exploit perfect filters. As a result, they generate sideband emissions, which causes performance degradation [9].

In [10], a gateway with both IEEE 802.15.4 and BLE interfaces is developed. A time-domain scheduling is made in the Linux kernel. However, the introduced scheduler does not consider transmission periods of BLE and IEEE 802.15.4. This scheduler can prevent the simultaneous transmissions, but it can lead to disconnections, because of missing command frames. Then the networks would require reconnections, which require the transmission of command frames again. Thus, this solution increases the transmission overhead and decreases the communication reliability. Our time-domain scheduler does not lead to disconnections, therefore it provides more efficient and reliable connections.

The aforementioned studies provide in-depth knowledge about CTI, and cooperative and non-cooperative coexistence methods between different standards. However, to the best of our knowledge, this paper is the first publication that proposes time-domain cooperative coexistence mechanisms between BLE and IEEE 802.15.4 networks without disconnections.

## III. Background

In this section, the essential characteristics of BLE and IEEE 802.15.4 are briefly reviewed.

### A. Bluetooth Low Energy

BLE is a low-power wireless networking protocol that provides connectivity with small power in short distances. It has 40 back to back channels in the 2.4 GHz ISM band, each with 2 MHz bandwidth. Three of the less congested channels are used as advertising channels, while the other 37 channels are used as data channels. BLE uses adaptive frequency hopping in which the transmission channel changes after every Connection Event (CE) and the BLE devices automatically black list the low quality channels. This way the BLE network avoids using highly interfered channels.

BLE sends data in two different ways: connectionless broadcasting and connection-oriented periodic data exchange. In this paper, we do not consider connectionless broadcasting mode of BLE, since it does not use duty cycling and it is not time structured. In the connection oriented mode, a central node (i.e., the master) and at least one peripheral device (slave) should be connected. After the connection is established, time is divided into periodic Connection Intervals (CIs). Each CI includes a CE, which is the data transmission period, and a sleeping time. Fig. 2 illustrates the structure of communications in connection-oriented BLE.

A CI can have a value between $7.5ms$ and $4s$, and it should be a multiple of $1.25ms$. Eqn. 1 [1] presents the calculation of CI.

$$\begin{aligned} CI &= 1.25\ ms \times K \\ 7.5\ ms &\leq CI \leq 4000\ ms, \quad K \in \mathcal{N} \end{aligned} \tag{1}$$

Each CI starts with a CE including data and acknowledgement packets. The radio enters the sleeping period after the CE finishes. A CE is not limited to only one packet. However, most of the BLE devices in the market have some limitations in this regards, mainly because of memory and power efficiency reasons. In

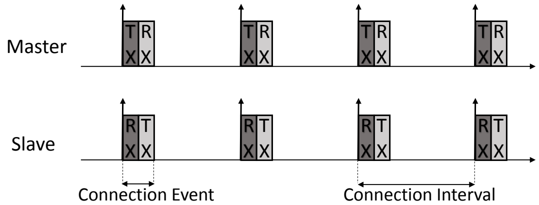



Fig. 2. Time-domain structure of communications in BLE

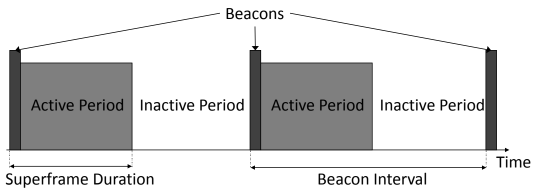



Fig. 3. Time-domain structure of beacon-enabled IEEE 802.15.4

this paper, we assume that only one packet from the central node to each peripheral, and one packet from each peripheral to the central node is transmitted in each CE. Also, the CE of each peripheral is scheduled $5ms$ apart from that of the other peripherals.

### B. IEEE 802.15.4

IEEE 802.15.4 is a physical and MAC layer standard developed for low-rate wireless personal area networks. It operates in one of the 16 channels in 2.4 GHz band, each with 2MHz bandwidth and 5MHz channel spacing. Unlike BLE, IEEE 802.15.4 does not provide channel hopping, therefore a selected channel is not changed.

IEEE 802.15.4 has two different operational modes: beacon-enabled and non beacon-enabled modes. The non beacon-enabled mode does not implement duty cycling and it is not time structured. Therefore, this mode is beyond the scope of this paper. Beacon-enabled mode divides the time to Beacon Intervals (BIs). Each BI is divided into a Superframe Duration (SD) and a sleep period. The structure of BIs and superframes of this standard is shown in Fig. 3. The BI and SD are given in Eqn. 2 [2], where BO and SO represent beacon-order and superframe-order as two integer parameters used in the standards for configuration of the frames.

$$\begin{aligned} BI &= 15.36\ ms \times (2^{BO}) \\ SD &= 15.36\ ms \times (2^{SO}) \\ 0 \leq SO &\leq BO \leq 14 \end{aligned} \tag{2}$$

## IV. Time Domain Cooperative Coexistence

The connection oriented mode of BLE and the beacon-enabled mode of IEEE 802.15.4 provide time structured energy efficient periodical communication with duty cycles. It is possible to schedule transmissions of one radio while the other one sleeps and vice versa, by using cooperation between the radios. This type of scheduling can be implemented in the network as illustrated in Fig. 4, which shows a gateway with both radios and multiple end devices in each network.

Simultaneous transmissions can be avoided by placing the transmissions of one network in the inactive

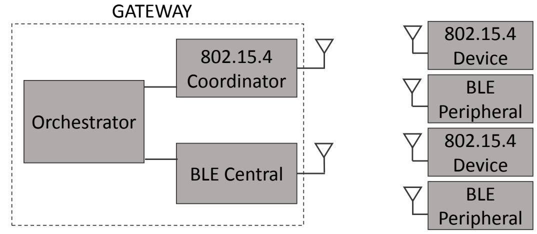
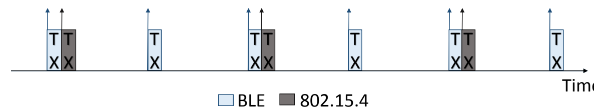
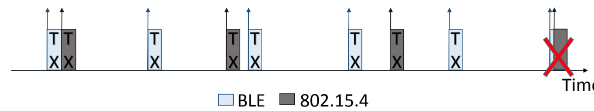



Fig. 4. Network structure for cooperative coexistence solution




(a) A period divides the other one




(b) A period does not divide the other one

Fig. 5. Periodic BLE and IEEE 802.15.4 transmissions

period of the other one. If the transmission periods are aligned at the beginning of the connections and if one period divides the other one, simultaneous transmissions can be avoided. However, if one period does not divide the other one, the connections loose their alignment after some periods and simultaneous transmissions occur. These scenarios are demonstrated in Fig. 5.

The number of BI and CI pairs that succeed the alignment given in Fig. 5(a) is very low, since the BI and CI multipliers, 15.36 ms and 1.25 ms, do not have a common divisor. Only if the CI is 3840 ms, which is the division of the least common multiple of 1.25 and 15.36 to the greatest IEEE 802.15.4 duty cycle ($2^{-1}$), a none-overlapping alignment is possible. Therefore, this is not a feasible solution to most of the CI and BI pairs. If one period is not a multiple of the other, we propose to implement coexistence by realignment before the active regions of the networks overlap. For this, we may adapt BLE transmissions to the IEEE 802.15.4 timing schedule or the other way around. Both of these methods require the IEEE 802.15.4 coordinator and the BLE central modules to cooperate by informing the orchestrator module of the gateway about their time structures. Then, using this information as an input to the coexistence algorithms, the orchestrator calculates whether a change in the transmission periods is necessary or not. If this is necessary, the orchestrator informs back the IEEE 802.15.4 coordinator and the BLE central blocks about it. In the following section, we discuss the two coexistence approaches. Later on, we evaluate their performance in real network setups.

### A. Coexistence using BLE as the Adapting Network

In this approach, we align the CEs of the BLE network when we predict that it is going to overlap with the superframes of the IEEE 802.15.4 network. The realignment is implemented using the connection update procedure of BLE, as defined in the standard.

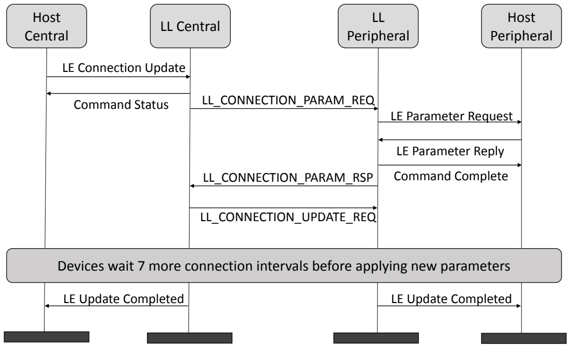
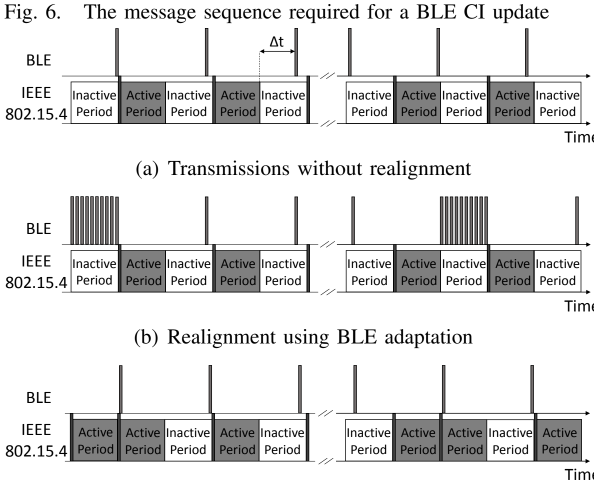



Fig. 6. The message sequence required for a BLE CI update




(a) Transmissions without realignment

(b) Realignment using BLE adaptation

(c) Realignment using IEEE 802.15.4 adaptation

Fig. 7. BLE and IEEE 802.15.4 transmissions without and with realignments for $BI > CI$

Prior to the update of the connection, the central and the peripheral devices exchange three control messages. The new connection parameters are used after seven more CIs. Therefore, the update procedure should be initiated at least 10 CIs before the preferred update moment. This value can increase if some of the messages do not reach to the receiver and need to be retransmitted. The complete connection update procedure is depicted in Fig. 6.

The realignment is done because the active regions of BLE and IEEE 802.15.4 shift over time in relation to each other. The direction of this shift depends on the proportion of BI and CI values. For example, in Fig. 7(a) the BLE CEs shift to the left with respect to the IEEE 802.15.4 beacons after each period. It is because $BI > CI$. If $CI > BI$, the direction of the shifting changes to the right.

The BLE need to be realigned, if the next expected overlap of the active regions is closer than 10 periods. This time can be predicted using the time difference between the CE of BLE and the active period of IEEE 802.15.4 on the direction of the shifting. This time difference is represented by $\Delta t$, and it is shown in Fig. 7(a). During the realignment, the CI value is decreased to one tenth of the required shift. The amount of realignment depends on the direction of shifting. If

**Algorithm 1** Algorithm for BLE adaptation

**Input:** $CI_{def}$, $CI_{cur}$, $SD$, $BI$, $\Delta t$
**Output:** $CI_{cur}$
**if** $CI_{cur} == CI_{def}$ **then**
  **if** $BI > CI_{def}$ **then**
    **if** $\Delta t + margin < (BI - CI_{def}) \times 10$ **then**
      $CI_{cur} = f_{1.25}\big((BI - SD)/10\big)$
    **end if**
  **else**
    **if** $\Delta t + margin < (CI_{def} - BI) \times 10$ **then**
      $CI_{cur} = f_{1.25}\big(SD/10\big)$
    **end if**
  **end if**
**else**
  $CI_{cur} = CI_{def}$
**end if**

**Algorithm 2** Algorithm for IEEE 802.15.4 adaptation

**Input:** $BI_{def}$, $BI_{cur}$, $SD$, $CI$, $\Delta t$
**Output:** $BI_{cur}$
**if** $BI_{cur} == BI_{def}$ **then**
  **if** $\Delta t < |BI_{def} - CI|$ **then**
    $BI_{cur} = SD$
  **end if**
**else**
  $BI_{cur} = BI_{def}$
**end if**

the direction is to the left (Fig 7(a)), the amount of shifting should be equal to the length of the inactive period of IEEE 802.15.4, while for the reverse case it should be equal to the length of the active period of IEEE 802.15.4. In order to change the CI back to its original value following the realignment, the second connection update should be initiated straightaway after the first CE of the realignment process. The procedure is given in Algorithm 1, where $CI_{def}$ and $CI_{cur}$ refer to the default and current value of the CI, respectively. Function $f_{1.25}(x)$ returns the maximum value lower than $x$ that is a multiple of $1.25\ ms$. Fig. 7(b) illustrates this process.

### *B. Coexistence using IEEE 802.15.4 as the Adapting Network*

This solution uses the properties of the beacon interval of the IEEE 802.15.4 standard in order to avoid collisions. The IEEE 802.15.4 network applies realignment if the next superframe is expected to overlap with the CE of BLE. This overlapping can be predicted using the same $\Delta t$ value that is defined in Section IV-A. If $\Delta t$ is lower than the difference between CI and the default value of BI ($BI_{def}$), BI should be updated, to avoid overlapping in the next period. Unlike in the BLE adaptation, a margin to detect overlapping is not needed. For the IEEE 802.15.4 adaptation, the amount of realignment is set equal to SD, since this amount of shifting aligns the next CE to the optimum place. The second update command is called immediately after the first one is executed, because just one shorter BI suffices. The IEEE 802.15.4 adaptation mechanism is given in Algorithm 2 and presented in Fig. 7(c).

TABLE I. TEST PARAMETERS FOR BLE

| | |
|---|---|
| Number of peripherals | 2 |
| Connection Interval | 950 ms |
| Traffic | 1 packet / CE |
| Packet length | 37 bytes |
| Packet transmit duration | 0.4 ms |
| Packet type | Notification |
| Number of data channels | 2, 5, 16, 37 |

TABLE II. TEST PARAMETERS FOR IEEE 802.15.4

| | |
|---|---|
| Number of end nodes | 2 |
| Beacon Interval | 983.04 ms ($BO = 6$) |
| Superframe Duration | 491.52 ms ($SO = 5$) |
| Traffic | Subsequent transmissions |
| Frame length | 113 byte |
| Packet transmit duration | 4 ms |
| Average inter packet spacing | 4 ms |
| Medium access | Slotted CSMA / CA |
| Number of channels | 1 |

## V. PERFORMANCE EVALUATION

In this section, we first introduce our test setup and then analyze the achieved results.

### A. Test Setup

The network is designed as in Fig. 4. The end devices are connected to a gateway that includes transceivers of both BLE and IEEE 802.15.4 technologies. Two IEEE 802.15.4 end nodes and two BLE peripherals are used. To prevent uncontrolled interference, the tests are done in a shielded room. Texas Instruments SensorTag CC2650 [11] and ATMEL Atmega256RFR2 XPro [12] devices are used as the BLE and IEEE 802.15.4 devices, respectively. The distance between any two devices in the network is kept around 20 $cm$. The other parameters are given in Table I and Table II.

In the experiments, the IEEE 802.15.4 link is saturated and the effect of this densely occupied link on the BLE link is observed. Since BLE is affected more by the interference of IEEE 802.15.4 than vice versa, the IEEE 802.15.4 network is used as the interfering network and the BLE network as the affected [3]. Therefore, this scenario requires more improvement in the reliability than the reverse scenario. The effect of interference is evaluated using Packet Error Rate (PER) and burst packet losses. PER is the percentage of dropped packets to the total transmitted packets, while burst packet losses is the number of consecutive packet drops. Also, the energy consumption overhead of the gateway node for applying the proposed coexistence solutions is analyzed. Based on the standard, the IEEE 802.15.4 channel operates in only one channel while, according to the BLE standard, the number of active BLE data channels is from 2 to 37 channels. We tried four different number of data channels for the BLE network (i.e., 2, 5, 16, and 37 channels). In each case, the IEEE 802.15.4 channel was one of the channels used by BLE.

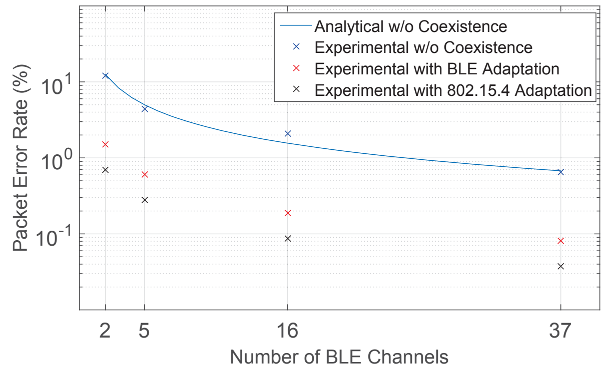



Fig. 8. PER of BLE Links for analytical and experimental results

### B. Result Analysis

When one of the BLE and IEEE 802.15.4 periods is not a multiple of the other one, simultaneous transmissions take place, as illustrated in Fig. 5. Since, in our experiments, periods of BLE and IEEE 802.15.4 are 950 $ms$ and 983.04 $ms$ respectively, the start of the active region of BLE shifts 33.04 $ms$ earlier compared to that of IEEE 802.15.4 after each IEEE 802.15.4 period. In other words, $\Delta$t in Fig. 7(a) decreases 33.04 $ms$ after each period. Since the duty cycle of the IEEE 802.15.4 network is set to 50%, it is expected that half of the BLE transmissions occur during the active period of the IEEE 802.15.4 network, if a coexistence solution is not applied. Note that during the times when BLE and IEEE 802.15.4 active regions overlap, the transmissions can still be successful depending on two other factors. Firstly, if BLE and IEEE 802.15.4 packets are transmitted in different frequency channels, they do not collide. Secondly, if one radio is not transmitting because of its inter-frame spacing, it does not interfere with the transmission of the other radio.

The expected PER value of the BLE link can be calculated analytically as expressed in Eqn. 3, which considers BLE packets as infinitesimally small and equates the PER to the probability of IEEE 802.15.4 transmission in a specific channel at a specific instant. CH stands for the number of BLE channels. DC is the Duty Cycle of the IEEE 802.15.4 network (i.e., SD divided by BI), and SAR is the Superframe Active Ratio, which gives the channel occupancy ratio during the active portion of the IEEE 802.15.4 network. SAR is determined by the inter-frame spacing specified in the standard and CSMA contention duration.

$$PER_{analytical} = \frac{1}{CH} \times DC \times SAR \qquad (3)$$

Using the parameters given in Table I and Table II, both DC and SAR values are 0.5. Fig. 8 shows the value of analytically expected PER for various number of BLE channels. This curve is validated with the experimental results, that are gathered without activating the coexistence algorithms. The slight difference between the $PER_{analytical}$ and the experimental results of the without coexistence case can be explained by the non-homogeneous traffic distribution of the BLE channel

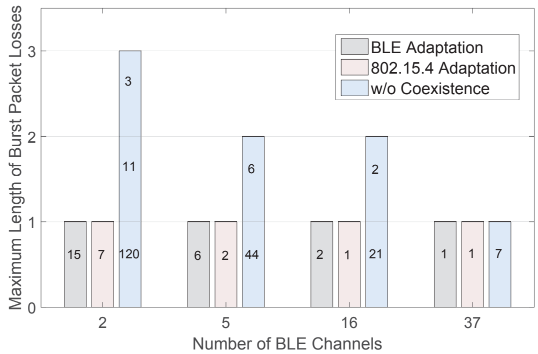



Fig. 9. Maximum length of burst and the number of losses for each length of burst for 1000 transmission attempts on a BLE link

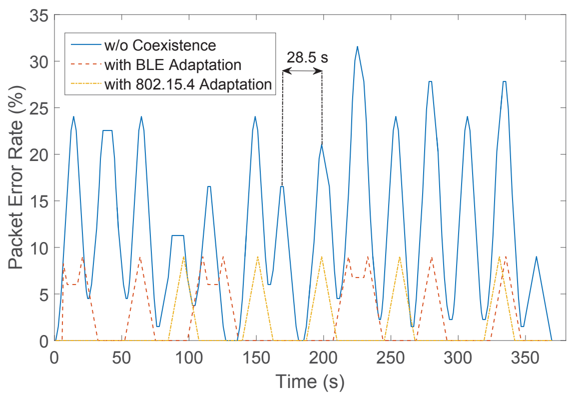



Fig. 10. PER of BLE links over time in two-channel experiments

hopping algorithm. In this algorithm, the probability of choosing a channel can vary up to 25% [13]. Therefore, the difference between the analytical curve, which does not consider the non-homogeneous distribution, and the relevant experimental results can differ up to 25%. Fig. 8 also includes the achieved PER of the BLE network in the experiments with the coexistence algorithms. Both coexistence algorithms result in a significant improvement in PER of the BLE network, especially if less BLE channels are being used.

Fig. 8 reveals the gain achieved by the proposed solutions on average PER of the BLE network, but it does not show the effect on the distribution of packet losses. Fig. 9 shows the improvement on the maximum length of burst packet losses, which is the maximum number of consecutive packet drops on a link. This improvement is vital, since the applications usually need to limit the disconnection duration. Also, this figure shows the number of burst losses for 1000 packet transmissions on the BLE link. As the number of BLE channels increases, not only the maximum length but also the repetition of burst errors decreases for each level. Fig. 10 demonstrates the change of PER of the BLE link over time, for the experiments with and without the proposed solutions, while only two channels of BLE link are used. This figure is created applying a linear weighted moving average filter with a window size of 20 transmissions. 15 consecutive BLE transmissions are expected to interfere with IEEE 802.15.4 transmissions while the next 15 transmissions are expected to not interfere. Consequently, the successive peaks in Fig. 10 have 30 CIs (28.5 $s$) distance from each other. Fig. 9 and Fig. 10 confirm that our coexistence algorithms not only decrease the average error rate, but also prevent error peaks. According to our experiments, the IEEE 802.15.4 adaptation is more reliable than the BLE adaptation method. However, the reliability of the BLE adaptation can be further improved by increasing the margin value that is introduced in Algorithm 1.

TABLE III. TIME AND CURRENT SPECIFICATION OF DEVICES

| Description | Notation | SensorTag [14] | Atmel [15] |
|---|---|---|---|
| Transmit current | $I_{tx}$ (mA) | 7.66 | 14.5 |
| Receive current | $I_{rx}$(mA) | 6.48 | 12.5 |
| Sleep current | $I_{sl}$(mA) | 0.001 | 0.4 |
| Transmit time | $t_{tx}$ (ms) | 0.5 | 4 |
| Receive time | $t_{rx}$(ms) | 2 | 4 |

### C. Energy Overhead Analysis

The average radio power consumption of both SensorTag and Atmel devices can be calculated using the current consumption and the time parameters of the standards. For this calculation, transmit, receive, and sleep states of the radios are considered.

In the case of BLE, the energy consumption in the CE ($E_{CE}$) and in the sleep duration ($E_{sl}$) are two components of the total energy consumption of a CI. Thus, the average power consumption of the BLE radio ($P_{ST}$), without the proposed cooperative coexistence solution, is given by Eqn. (6).

$$E_{CE} = V \times \left(I_{tx} \times t_{tx} + I_{rx} \times t_{rx}\right) \quad (4)$$

$$E_{sl} = V \times I_{sl} \times \left[CI - (t_{tx} + t_{rx})\right] \quad (5)$$

$$P_{ST} = \frac{E_{CE}+E_{sl}}{CI} \quad (6)$$

The power consumption of the BLE adaptation can be calculated by focusing on two different parts of the operation. As represented in Fig. 7(b), the BLE adaptation algorithm keeps its default CI value until the moment that overlap is predicted. The number of CIs before a shift point is $N = \frac{BI-SD}{BI-CI}$. When this shift point arrives, we need to have 10 shorter CI, as specified in Algorithm 1. The energy consumption during the sleep period of the shorter CIs ($E_{ssl}$) is calculated by Eqn. 7. Then, $E_{CE} + E_{ssl}$ provides the energy consumption of a short CI. Finally, the average power consumption of the BLE device with coexistence adaptation algorithm ($P_{ST,ad}$) is calculated by Eqn. 8.

$$E_{ssl} = V \times I_{sl} \times \left[\frac{BI-SD}{10} - (t_{tx} + t_{rx})\right] \quad (7)$$

$$P_{ST,ad} = \frac{N\times\left(E_{CE}+E_{sl}\right)+10\times\left(E_{CE}+E_{ssl}\right)}{(N\times CI)+(BI-SD)} \quad (8)$$

The average power consumption of the IEEE 802.15.4 operation is calculated using the Atmel radio state information. IEEE 802.15.4 includes periodic active and sleep time intervals. In our scenario, the active state is saturated with 4 ms of packet transmissions followed by 4 ms of inter-packet spacing. Therefore, the radio is in the transmit state during half of SD,

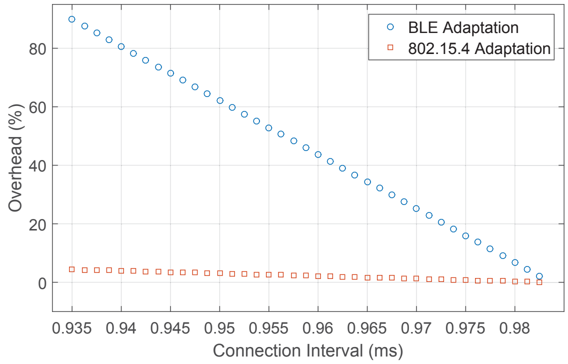



Fig. 11. Overhead of the algorithms for $BO = 6$ and $SO = 5$

and in the receive state during the other half. Eqn. 9 and Eqn. 10 give the energy consumption of the Atmel device in a SD ($E_{SD}$), and in the sleep period of the BI ($E_{sl}$). Eqn. 11 calculates the average radio power consumption ($P_{AT}$) when no adaptation mechanism is applied.

$$E_{SD} = V \times \left(I_{tx} \times \frac{SD}{2} + I_{rx} \times \frac{SD}{2}\right) \tag{9}$$
$$E_{sl} = V \times I_{sl} \times (BI - SD) \tag{10}$$
$$P_{AT} = \frac{E_{SD}+E_{sl}}{BI} \tag{11}$$

Just like the BLE adaptation, the IEEE 802.15.4 adaptation algorithm includes two states. In normal situation, the radio keep the default parameters until the shift point arrives after which it decreases BI to SD for one interval. The average power consumption of using the IEEE 802.15.4 adaptation ($P_{AT,ad}$) is given in (12). Since the shifting process includes only one shorter BI with $DC = 100\%$, the energy spent during shifting is equal to $E_{SD}$.

$$P_{AT,ad} = \frac{(N \times P_{AT} \times BI) + E_{SD}}{(N \times BI) + SD} \tag{12}$$

Eqn. 13 and Eqn. 14 give the amount of power overhead of the each coexistence solutions.

$$Overhead_{BLE} = \frac{P_{ST,ad}-P_{ST}}{P_{ST}} \tag{13}$$
$$Overhead_{802.15.4} = \frac{P_{AT,ad}-P_{AT}}{P_{AT}} \tag{14}$$

Both the BLE and the IEEE 802.15.4 adaptation algorithms impose some energy overhead on the gateway node, due to the extra transmissions they cause. Fig. 11 shows the overhead values when $BI = 983.04\ ms$ and $SD = 491.52\ ms$. The parameters given in Table I and Table II lead to 62% overhead for BLE adaptation and 3% for IEEE 802.15.4 adaptation.

Both coexistence algorithms improve transmission quality by decreasing the PER and burst errors. However, as Fig. 11 shows, the IEEE 802.15.4 adaptation is significantly more energy efficient than the BLE adaptation. This can be explained by the 10 packets limitation of the BLE adaptation, while IEEE 802.15.4 adaptation requires only one extra active region for realignment. Also, in a network with more end devices, the IEEE 802.15.4 adaptation is more favorable, because all IEEE 802.15.4 end devices follow a single BI, while in a BLE network the end devices can have different CIs. Still, the BLE adaptation may be preferred in specific network scenarios. For instance, it is more efficient to change the parameters of the BLE network, if the number of BLE end devices is significantly lower than the IEEE 802.15.4 end devices.

## VI. Conclusion

This paper has proposed two time-domain cooperative coexistence solutions for co-located BLE and IEEE 802.15.4 networks. The proposed algorithms predict packet collision times and avoid them by shifting the periodic transmissions. In one algorithm the BLE network adapts itself to the IEEE 802.15.4 while in the other algorithm the IEEE 802.15.4 network adapts. The real-world experiments show that the proposed algorithms achieve up to 12% improvement in packet delivery. Furthermore, the algorithms prevent burst errors.

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