

Cooperative coexistence of heterogeneous wireless sensor networks

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Cooperative Coexistence of Heterogeneous Wireless Sensor Networks

by

Onur Carhacioglu

Supervisors: Majid Nabi Najafabadi (TU/e), Pouria Zand (imec)

A thesis submitted in partial fulfillment for the
degree of Professional Doctorate in Engineering

in the
Electrical Engineering Department
Electronic Systems Group

February 2018

"If you think that the internet has changed your life, think again. The IoT is about to change it all over again!"

Brendan OBrien



EINDHOVEN UNIVERSITY OF TECHNOLOGY

Abstract

Electrical Engineering Department
Electronic Systems Group

Professional Doctorate in Engineering

by [Onur Carhacioglu](#)

Wireless Sensor Networks have already entered into our lives and they are expected to be even more widespread in the close future. The technologies of the future, such as self driving cars, smart cities, and smart homes require variety of Wireless Sensor Networks standards to operate in the same environment with high reliability. However, if these standards use the same ISM band, the network can suffer from Cross Technology Interference, which can decrease the reliability.

The main focus of this thesis is the Cross Technology Interference in 2.4 GHz. 2.4 GHz is an unlicensed, therefore highly occupied, ISM band. Efficient use of this band is of foremost importance. The most common 2.4 GHz Wireless Sensor Networks standards are BLE, IEEE 802.15.4, and TSCH.

This thesis makes the following contributions. Cooperative coexistence methods for BLE-IEEE 802.15.4, and BLE-TSCH networks are proposed. For heterogeneous BLE-IEEE 802.15.4 network, only time domain rescheduling methods are used. However, for heterogeneous BLE-TSCH network, both time and frequency domain rescheduling methods are discussed. The proposed solutions do not impose any protocol change. They use the MAC layer functions defined in these standards. The proposed solutions are tested using real hardware devices. In these tests, packet reception ratio is used as a performance metric, and energy overhead is used as a cost metric. The overall packet reception ratio improves up to 12 % for BLE-IEEE 802.15.4 network and 45.6 % for BLE-TSCH network.

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Abbreviations

ACK	A CKnowledgement
ASN	A bsolute S lot N umber
BI	B eacon I nterval
BLE	B luetooth L ow E nergy
BO	B eacon O der
CE	C onnection E vent
CI	C onnection I nterval
CSMA	C arrier S ense M ultiple A ccess
CTI	C ross T echnology I nterference
GCD	G reatest C ommon D ivisor
IoT	I nternet of T hings
LCM	L east C ommon M ultiple
MAC	M edium A ccess C ontrol
PER	P acket E rror R ate
RP	R aspberry P i
SD	S uperframe D uration
SO	S uperframe O der
TDMA	T ime D ivision M ultiple A ccess
TI	T exas I nstruments
TSCH	T ime S lotted C hannel H opping



To my family...

Chapter 1

Introduction

Since the introduction of internet, data communication devices such as smart phones, computers and tablets are essential parts of daily lives. Recently, with the emerge of IoT, the number of connected devices are expected to increase even further. A big amount of these devices are expected to be the nodes of Wireless Sensor Networks. These nodes convert the physical conditions of the environment to digital data. Then, this data is transmitted to a central processor, which analyses this input and takes smart decisions.

The communication of the nodes of WSNs is standardized by many specifications, such as WiFi [2], IEEE 802.15.4 [3], BLE [4], TSCH [5], and LoRa [6]. Each one of these standards are superior to the others in some specific use cases. For example, LoRa provides connectivity for smart city applications, while BLE connects the nodes within the short range. In order to integrate benefits of these standards, heterogeneous WSNs are used. In such networks, more than one communication standard is used.

This thesis focuses on increasing the reliability of communication in heterogeneous WSNs. The reliability of communication is important for several reasons. Firstly, a reliable wireless link requires less number of retransmissions, therefore provides better power efficiency. Since most of the nodes of a WSN have small batteries, improvements in the reliability have a significant impact on the lifetime of the WSN. Secondly, high reliability is a common application layer requirement. For example, in-vehicle WSNs require high reliability, because any failure can cause life threading accidents. Thirdly, a more reliable connection provides less latency and jitter, that are two of the important performance metrics of the networks. Due to these reasons, the link reliability in WSNs requires especial consideration.

WSN standards have their own MAC layer mechanisms to prevent packet collisions. For example, BLE uses channel hopping, and IEEE 802.15.4 uses CSMA protocol. However, these mechanisms are designed to prevent collisions inside the network. In a heterogeneous WSN, the transmissions of one network, e.g. BLE, can interfere with the transmissions of another network, e.g. TSCH. This type of interference is named Cross Technology Interference (CTI).

The main focus of this thesis is on improving the reliability of the links of heterogeneous WSNs, by decreasing the deteriorating effect of CTI on 2.4 GHz ISM band. We study the CTI of BLE, TSCH, and IEEE 802.15.4 standards, since these are the most widely used ones. Many solutions are proposed for the coexistence of these standards. The proposed solutions significantly improve packet reception ratio, therefore provide reliable connections.

The rest of this chapter is organized as follows. Section 1.1 gives some example WSN applications as motivations to this work. Section 1.2 explains two different game theoretic type of coexistence: cooperative and non-cooperative. Section 1.4 describes the thesis organization.

1.1 Heterogeneous WSN Examples

1.1.1 Home networks

Body area networks can be used to monitor and improve the condition of the patients. The nodes of these networks can include motion, ECG, pulse, and blood pressure sensors. The combined data gathered from these devices can be periodically sent to doctors. Since all of these devices are attached to the body of the same person, the distance between each node is low. Therefore, a long communication range is not necessary. On the other hand, higher data rate is more preferable. Due to these reasons, a technology standard such as BLE is a good candidate for wireless body area networks.

In-home environmental sensor networks can be used to control the activity of different household tools, such as oven, microwave, air conditioner, lights etc. The range requirement for this application is higher than the body area networks, but it is not very high as well. IEEE 802.15.4 can be used for such applications.

In [1], a heterogeneous WSN scenario, which requires the operation of both body area network and in-home environmental sensor network, is created. This type of heterogeneous WSNs require coexistence of BLE and IEEE 802.15.4 radios. However, both of

them use the same 2.4 GHz transmission frequency, and inter-operation of these protocols require a reliable coexistence solution. The solutions proposed in Chapter 2 can be used to improve the performance of this network.

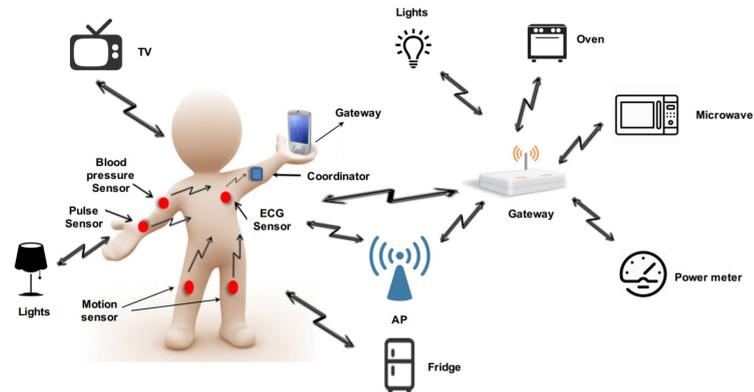


FIGURE 1.1: Heterogeneous home network [1]

1.1.2 Vehicular networks

The modern cars include a lot of wired connection, which increase total weight and oil consumption. WSNs can replace some of these wires, which makes it an energy efficient and environment friendly solution. Since TSCH provides reliable communication, it is a good candidate for in-vehicular networks. Also, BLE is a good candidate, because most of the modern cell phones have Bluetooth radio, therefore BLE can provide easy connectivity for the user. For some scenarios, it is better to employ both TSCH and BLE, in order to use their individual benefits. For example, a smart vehicle can include TSCH sensors for critical connections, e.g. brakes, while it uses BLE sensors for less critical but more user friendly connections, e.g. the water level of the wiper. The brakes require high reliability, because any delay or missing data can cause life threatening accidents. The water level of the wiper does not cause life threatening accidents, but it is more handy and easy to remember to monitor this level on the cell phone.

Both TSCH and BLE operate in 2.4 GHz frequency band. In order to use them in the same environment, CTI must be eliminated [7]. In Chapter 3, some solutions are proposed for this problem.

1.2 Cooperative and Non-cooperative Coexistence

In this thesis, cooperative methods are used to mitigate CTI. Cooperative coexistence requires exchange of information between the networks. This information can be about the future transmission time, the link statistics, or something else, which might be useful for the other network. After the reception of this information, the networks can make some changes in their future transmissions, in order to optimize the performance.

In the non-cooperative scenario, the networks do not exchange any information. A network might not even consider the effect of CTI. The non-cooperative networks can also cope with CTI, by analyzing and predicting the medium. As the prediction improves, the performance against the CTI also improves. However, their performance cannot exceed the performance of cooperative networks.

1.3 Contributions

This thesis makes the following contributions.

In Chapter 2,

- Two time domain cooperative methods are proposed for coexistence of BLE and IEEE 802.15.4 networks. One of them uses BLE as affecting network, while the other one uses IEEE 802.15.4.
- The performance of the proposed solutions is tested using real hardware devices. In these tests, PER and burst error length are used as performance metrics.
- The energy overheads of the proposed solutions are calculated.

In Chapter 3,

- Four cooperative methods are proposed for coexistence of BLE and TSCH networks.
- The performance of the proposed solutions is tested using real hardware devices. In these tests, PER is used as a performance metric.
- The energy overhead of the fourth method is measured by experiments.

The work presented in this thesis is also used in the following publications.

- Onur Carhacioglu, Pouria Zand, and Majid Nabi. Time-Domain cooperative coexistence of BLE and IEEE 802.15.4 networks. In 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC) - Track 3 on "Mobile and Wireless Networks" (IEEE PIMRC 2017 Track 3), Montreal, Canada, October 2017. [Published]
- Onur Carhacioglu, Pouria Zand, and Majid Nabi. Cooperative Coexistence of BLE and Time Slotted Channel Hopping Networks. In 2018 IEEE 29th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC) - Track 3 on "Mobile and Wireless Networks" (IEEE PIMRC 2018 Track 3), Bologna, Italy, September 2018. [Submitted]

1.4 Thesis Organization

This thesis includes the research results of Professional Doctorate in Engineering (PDEng) study in Eindhoven University of Technology (TU/e). The research is conducted with the cooperation of TU/e and IMEC NL. The research includes two projects: coexistence of BLE and IEEE 802.15.4, and coexistence of BLE and TSCH. In both of these projects, cooperative coexistence solutions are proposed for 2.4 GHz collocated WSNs.

In Chapter 2, coexistence of BLE and IEEE 802.15.4 networks is studied, and two algorithms are proposed. Later in this chapter, these algorithms are tested using real world experiments. Finally, the energy efficiency of these algorithms are compared. In Chapter 3, coexistence of BLE and TSCH networks is studied. Four different solutions are proposed. For the tests and the energy efficiency calculations, a similar method with the previous chapter is used. In Chapter 4, the thesis is concluded and the final remarks are given.

Chapter 2

Coexistence of BLE and IEEE 802.15.4 Networks

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 chapter, 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%.

2.1 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 [4] and IEEE 802.15.4 [3]. In addition to the single operation of each of these standards, some applications require inter-operation of them in a heterogeneous

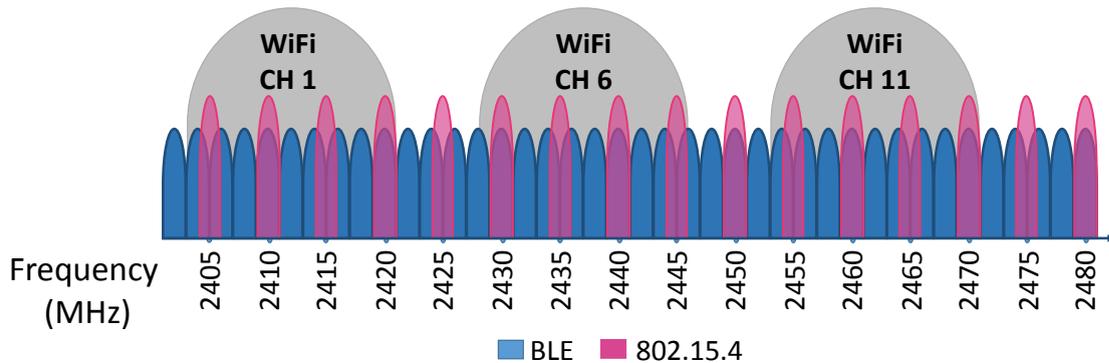


FIGURE 2.1: Channels of BLE, IEEE 802.15.4, and WiFi in 2.4 GHz

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 [8].

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. 2.1. 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.

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 [9], in which the radios share their transmission state with each other, or without cooperation [10], 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 [11]. 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 thesis, 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 chapter is organized as follows. Section 2.2 will discuss the related work on the coexistence of various wireless technologies. Section 2.3 offers the necessary background knowledge about the standards. The proposed coexistence mechanisms are presented in Section 2.4. Section 2.5 describes the experimental setup and the achieved results. Section 2.6 presents our conclusions.

2.2 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 [12] 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 [8], 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 versa. 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 [8] and [12] point out the interference problem, however they fail to provide any coexistence solution.

In [11], 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 [13], 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 [11] and [13] 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 [14].

In [15], 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 is the first work that proposes time-domain cooperative coexistence mechanisms between BLE and IEEE 802.15.4 networks without disconnections. Some of the contents of this work is published in our paper, [16].

2.3 Background

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

2.3.1 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

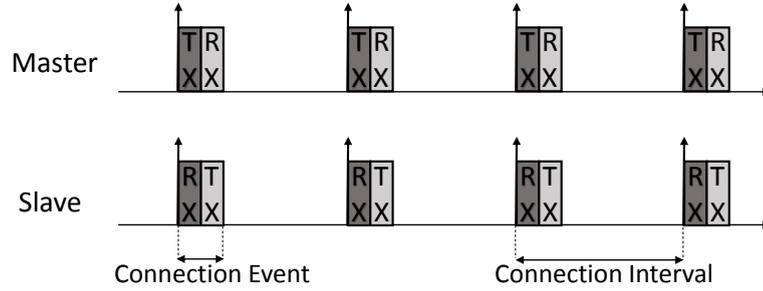


FIGURE 2.2: Time-domain structure of communications in BLE

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 chapter, 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. 2.2 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. 2.1 [4] presents the calculation of CI.

$$\begin{aligned}
 CI &= 1.25 \text{ ms} \times K \\
 7.5 \text{ ms} &\leq CI \leq 4000 \text{ ms}, \quad K \in \mathcal{N}
 \end{aligned}
 \tag{2.1}$$

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 this chapter, 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.

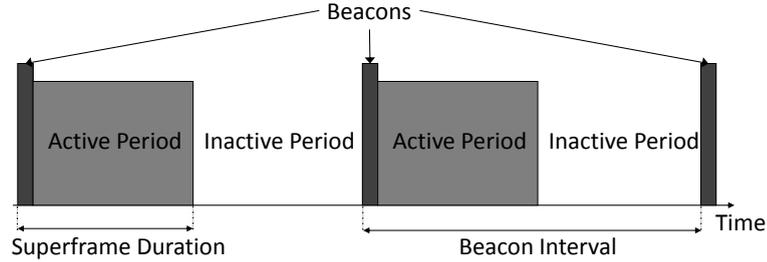


FIGURE 2.3: Time-domain structure of beacon-enabled IEEE 802.15.4

2.3.2 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 thesis. 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. 2.3. The BI and SD are given in Eqn. 2.2 [3], where BO and SO represent beacon-order and superframe-order as two integer parameters used in the standards for configuration of the frames.

$$\begin{aligned}
 BI &= 15.36 \text{ ms} \times (2^{BO}) \\
 SD &= 15.36 \text{ ms} \times (2^{SO}) \\
 0 &\leq SO \leq BO \leq 14
 \end{aligned}
 \tag{2.2}$$

2.4 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. 2.4, which shows a gateway with both radios and multiple end devices in each network.

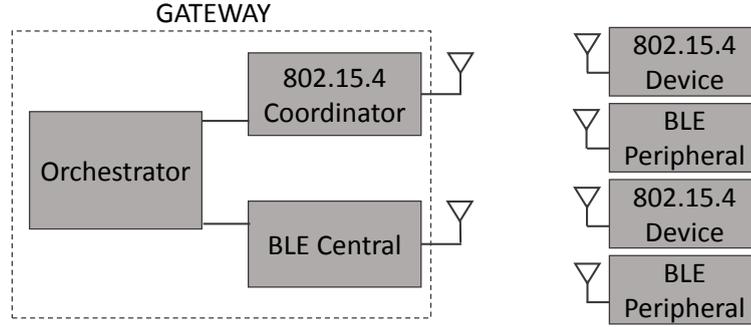


FIGURE 2.4: Network structure for cooperative coexistence solution

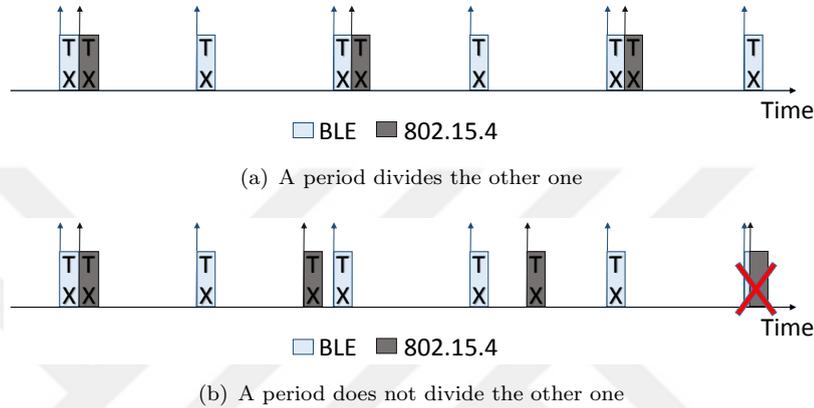


FIGURE 2.5: Periodic BLE and IEEE 802.15.4 transmissions

Simultaneous transmissions can be avoided by placing the transmissions of one network in the inactive 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 lose their alignment after some periods and simultaneous transmissions occur. These scenarios are demonstrated in Fig. 2.5.

The number of BI and CI pairs that succeed the alignment given in Fig. 2.5(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.

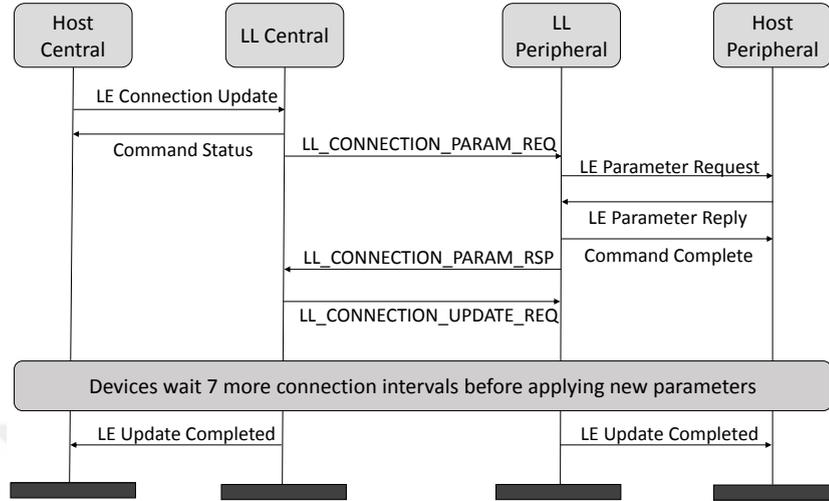


FIGURE 2.6: The message sequence required for a BLE CI update

2.4.1 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. 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. 2.6.

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. 2.7(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 Δt , and it is shown in Fig. 2.7(a). During the realignment, the CI value is decreased to one tenth of the required shift. The amount

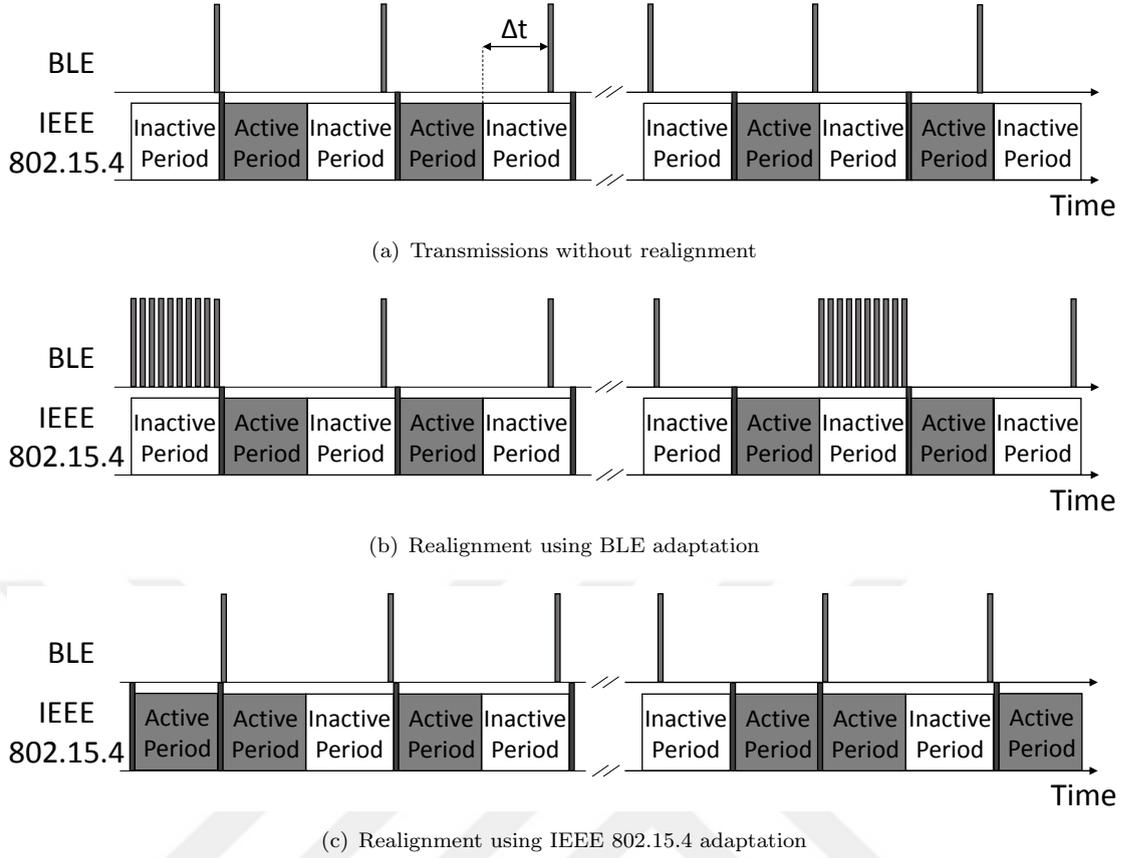


FIGURE 2.7: BLE and IEEE 802.15.4 transmissions without and with realignments for $BI > CI$

Algorithm 1 Algorithm for BLE adaptation

Input: CI_{def} , CI_{cur} , SD , BI , Δt

Output: CI_{cur}

```

1: if  $CI_{cur} == CI_{def}$  then
2:   if  $BI > CI_{def}$  then
3:     if  $\Delta t + margin < (BI - CI_{def}) \times 10$  then
4:        $CI_{cur} = f_{1.25}((BI - SD)/10)$ 
5:     end if
6:   else
7:     if  $\Delta t + margin < (CI_{def} - BI) \times 10$  then
8:        $CI_{cur} = f_{1.25}(SD/10)$ 
9:     end if
10:  end if
11: else
12:    $CI_{cur} = CI_{def}$ 
13: end if

```

of realignment depends on the direction of shifting. If the direction is to the left (Fig 2.7(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

Algorithm 2 Algorithm for IEEE 802.15.4 adaptation

Input: BI_{def} , BI_{cur} , SD , CI , Δt
Output: BI_{cur}

```

1: if  $BI_{cur} == BI_{def}$  then
2:   if  $\Delta t < |BI_{def} - CI|$  then
3:      $BI_{cur} = SD$ 
4:   end if
5: else
6:    $BI_{cur} = BI_{def}$ 
7: end if

```

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. 2.7(b) illustrates this process.

2.4.2 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 Δt value that is defined in Section 2.4.1. If Δt 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. 2.7(c).

2.5 Performance Evaluation

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

2.5.1 Test Setup

The network is designed as in Fig. 2.4. 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 [17] and

TABLE 2.1: 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 2.2: 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

ATMEL Atmega256RFR2 XPro [18] 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 2.1 and Table 2.2.

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 [8]. 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.

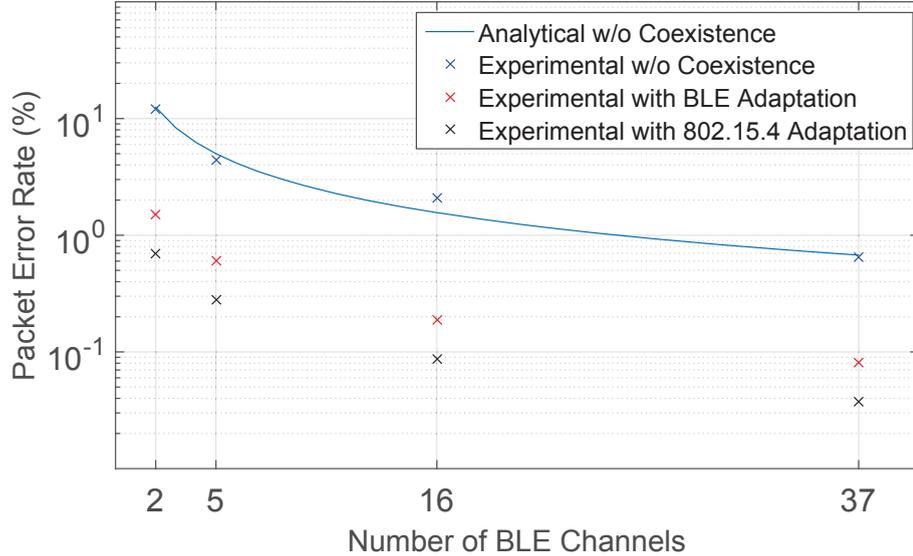


FIGURE 2.8: PER of BLE Links for analytical and experimental results

2.5.2 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. 2.5. 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, Δt in Fig. 2.7(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. 2.3, 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.

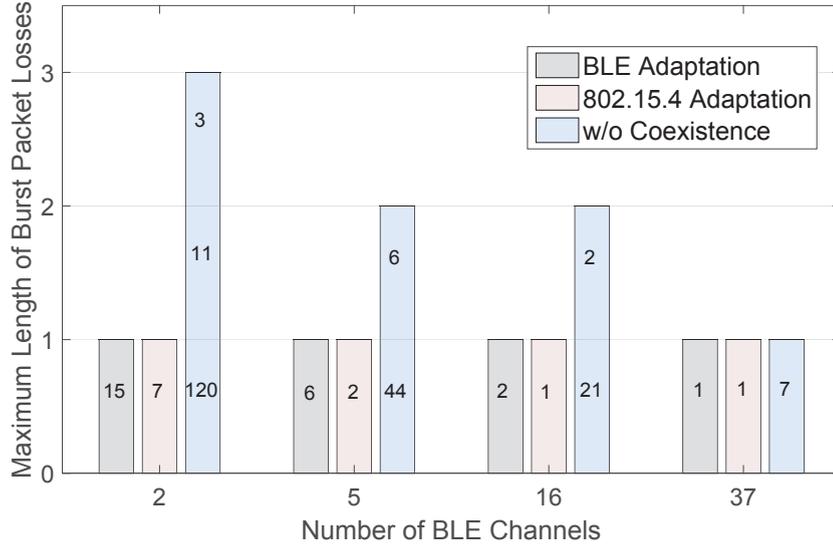


FIGURE 2.9: Maximum length of burst and the number of losses for each length of burst for 1000 transmission attempts on a BLE link

$$PER_{analytical} = \frac{1}{CH} \times DC \times SAR \quad (2.3)$$

Using the parameters given in Table 2.1 and Table 2.2, both DC and SAR values are 0.5. Fig. 2.8 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 hopping algorithm. In this algorithm, the probability of choosing a channel can vary up to 25% [19]. 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. 2.8 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. 2.8 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. 2.9 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

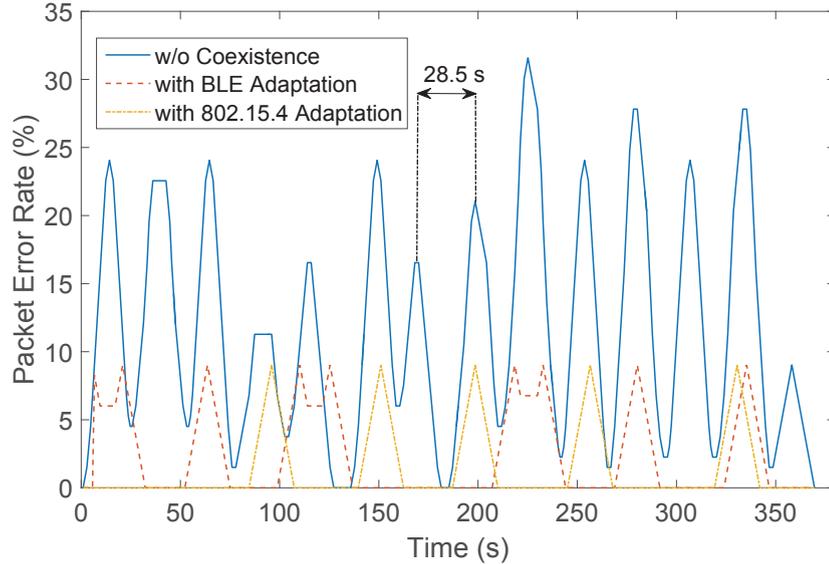


FIGURE 2.10: PER of BLE links over time in two-channel experiments

of burst errors decreases for each level. Fig. 2.10 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. 2.10 have 30 CIs (28.5 s) distance from each other. Fig. 2.9 and Fig. 2.10 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.

2.5.3 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. (2.6).

TABLE 2.3: Time and current specification of devices

Description	Notation	SensorTag [20]	Atmel [21]
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

$$E_{CE} = V \times (I_{tx} \times t_{tx} + I_{rx} \times t_{rx}) \quad (2.4)$$

$$E_{sl} = V \times I_{sl} \times [CI - (t_{tx} + t_{rx})] \quad (2.5)$$

$$P_{ST} = \frac{E_{CE} + E_{sl}}{CI} \quad (2.6)$$

The power consumption of the BLE adaptation can be calculated by focusing on two different parts of the operation. As represented in Fig. 2.7(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. 2.7. 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. 2.8.

$$E_{ssl} = V \times I_{sl} \times \left[\frac{BI-SD}{10} - (t_{tx} + t_{rx}) \right] \quad (2.7)$$

$$P_{ST,ad} = \frac{N \times (E_{CE} + E_{sl}) + 10 \times (E_{CE} + E_{ssl})}{(N \times CI) + (BI - SD)} \quad (2.8)$$

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, and in the receive state during the other half. Eqn. 2.9 and Eqn. 2.10 give the energy consumption of the Atmel device in a SD (E_{SD}), and in the sleep period of the BI (E_{sl}). Eqn. 2.11 calculates the average radio power consumption (P_{AT}) when no adaptation mechanism is applied.

$$E_{SD} = V \times \left(I_{tx} \times \frac{SD}{2} + I_{rx} \times \frac{SD}{2} \right) \quad (2.9)$$

$$E_{sl} = V \times I_{sl} \times (BI - SD) \quad (2.10)$$

$$P_{AT} = \frac{E_{SD} + E_{sl}}{BI} \quad (2.11)$$

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 (2.12). Since the shifting process includes only one shorter BI with $DC = 100\%$, the energy spent during shifting is equal to E_{SD} .

$$P_{AT,ad} = \frac{(N \times P_{AT} \times BI) + E_{SD}}{(N \times BI) + SD} \quad (2.12)$$

Eqn. 2.13 and Eqn. 2.14 give the amount of power overhead of the each coexistence solutions.

$$Overhead_{BLE} = \frac{P_{ST,ad} - P_{ST}}{P_{ST}} \quad (2.13)$$

$$Overhead_{802.15.4} = \frac{P_{AT,ad} - P_{AT}}{P_{AT}} \quad (2.14)$$

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. 2.11 shows the overhead values when $BI = 983.04 \text{ ms}$ and $SD = 491.52 \text{ ms}$. The parameters given in Table 2.1 and Table 2.2 lead to 62% overhead for BLE adaptation and 3% for IEEE 802.15.4 adaptation.

Efficiency of algorithms for other BO values

Fig. 2.12 provides a generalized version of Fig. 2.11 by giving the possible pairs of BLE and IEEE 802.15.4 periods and the energy efficiency of each pair, considering the duty cycle of IEEE 802.15.4 is $1/2$. The figure represents power efficiency of both BLE and IEEE 802.15.4 Adaptation algorithms, however the values change linearly between 0-4.5% for IEEE 802.15.4 Adaptation and 0-90% for BLE Adaptation. Since CI must be a multiple of 1.25 ms, there are jumps between the neighboring data points. However, as the BI increases, these jumps become invisible in the figure. The data set for a BI

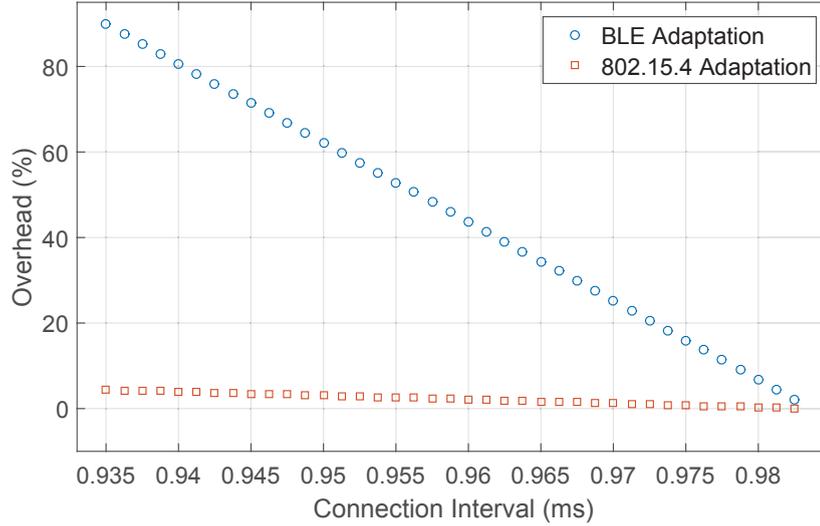


FIGURE 2.11: Overhead of the algorithms for $BO = 6$ and $SO = 5$

of 3932,16 ms is shorter, since the maximum possible CI is bounded by the standard to 4 s. The direction of shifting is the same of Fig. 2.7 for the values below one on the y axes. However, it is reverse for the values above one, therefore the initial alignment point and Δt of the algorithms should be chosen accordingly.

Fig. 2.11 and 2.12 provide compatible pairs and their power efficiency for 1/2 duty cycle of IEEE 802.15.4. Coexistence algorithms can also be applied to lower duty cycle values. As IEEE 802.15.4 duty cycle decreases, the number of compatible BI and CI pairs and their power efficiency increases. (2.15) provides the maximum number of connection intervals, N , before a realignment between the networks becomes necessary, by taking the length of SD, BI, CE and CI as input and optimizing the phase difference, P , between the start of the first BI and CI. If any combination of SD, BI, CE and CI can provide an N value greater than 10, then BLE Adaptation is possible for this combination. As N increases, the adaptation becomes more power efficient. Similar optimization can be created for IEEE 802.15.4 Adaptation by swapping SD with CE and BI with CI in (2.15). N can be lower than 10 for IEEE 802.15.4 Adaptation, since there is not a 10 packet limitation for this algorithm.

$$\max N$$

Subject To:

$$\begin{aligned} \forall k = 1..N, \\ SD < P + CI \times k \pmod{BI} \\ SD < P + CI \times k + CE \pmod{BI} \\ 0 < P < BI \end{aligned} \tag{2.15}$$

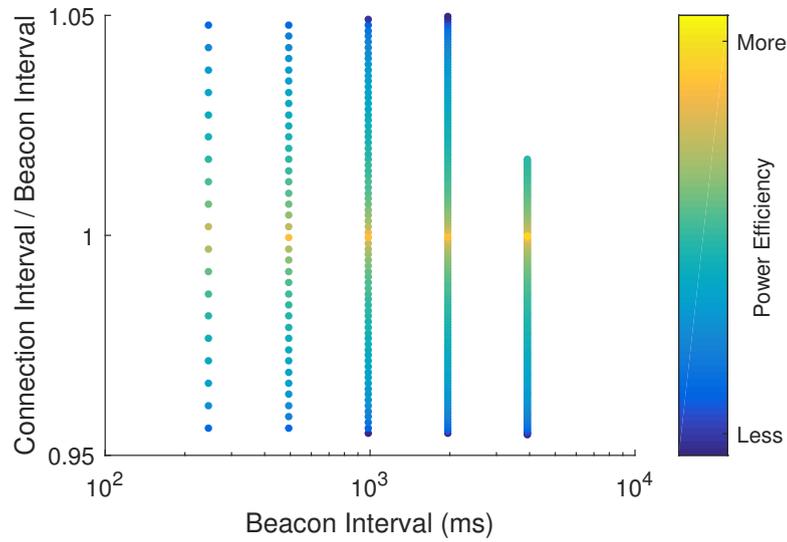


FIGURE 2.12: Compatible pairs and their energy consumption for 1/2 duty cycle on IEEE 802.15.4 link

Discussion

Both coexistence algorithms improve transmission quality by decreasing the PER and burst errors. However, as Fig. 2.11 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.

2.6 Conclusion

This chapter 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.

Chapter 3

Coexistence of BLE and TSCH Networks

Abstract

BLE and TSCH are two of the most commonly used wireless sensor networks standards. They share the same 2.4 GHz ISM band. The use of both of these standards in a heterogeneous WSN can provide extra functionality. However, such networks suffer from CTI, which decreases the reliability of the network. To solve this problem, we propose four cooperative coexistence solutions for collocated BLE-TSCH networks. These solutions use a scheduling matrix to model the resource usage of the networks. Then, the overlaps in this matrix are eliminated by rescheduling the transmissions of the networks. The proposed solutions do not impose any protocol change. The performance of them is evaluated using real hardware devices. The real world experiments show that all of the proposed solutions decrease PER more than half. Up to 45.6 % PER improvement is observed in the experiments.

3.1 Introduction

With the emergence of IoT, the number of connected devices has rapidly grown. The communication between these devices are standardized by many specifications. These specifications provide connectivity for special use cases. For indoor wireless sensor networks, the most widely used specifications are IEEE 802.15.4 and BLE. TSCH is an amendment to the MAC operation of IEEE 802.15.4, which improves reliability.

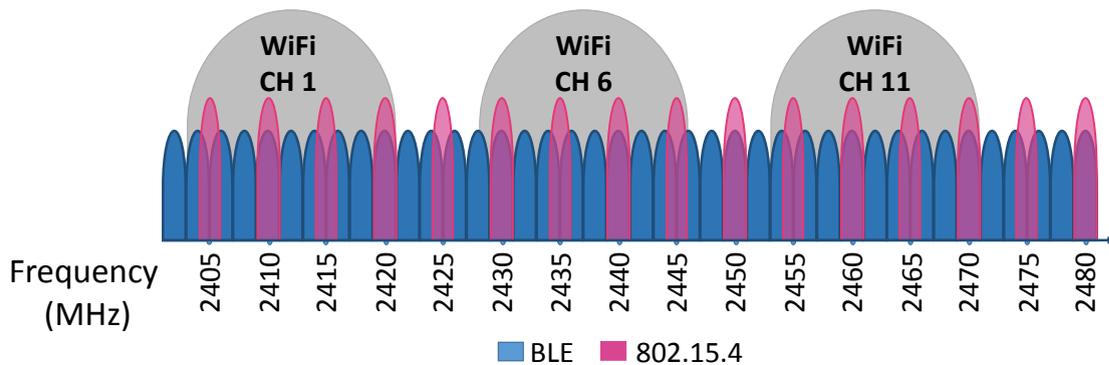


FIGURE 3.1: Channels of BLE, IEEE 802.15.4, and WiFi in 2.4 GHz

Most of the IoT applications require highly reliable communication. For example, in-vehicular networks require high reliability, since any missing data can cause life threatening accidents. High reliability is also important in industrial automation, because failure in a small part can damage the whole system.

Both TSCH and BLE are equipped with MAC layer mechanisms to provide high reliability. TSCH allocates periodic timeslots for each pair in the network. Furthermore, each timeslot uses a different frequency channel after each period. BLE uses CIs to provide periodic transmissions. Also, BLE uses adaptive frequency hopping in which the transmission channel changes after every CI. Therefore, both TSCH and BLE use methods, which are combinations of TDMA and FDMA mechanisms. While these mechanisms prevent packet collisions in the network, they fail to provide highly reliable connections under CTI.

A smart gateway can support both BLE and TSCH standards, in order to connect to the end devices of both technologies. However, both TSCH and BLE use the same 2.4 GHz ISM band. The channels of WiFi, BLE, and IEEE 802.15.4 (TSCH) are shown in Fig. 3.1. If both of these networks are used in the same location, CTI will significantly decrease the reliability of these networks. In order to cope with CTI, a coexistence mechanism is required.

Coexistence mechanisms are divided into two groups: non-cooperative and cooperative. This categorization reflects the ways in which they obtain information. In non-cooperative coexistence, a network predicts the transmission of the other network. Based on this prediction, the network schedules its own transmission. In cooperative coexistence, the networks exchange their transmission schedules. In this way, the networks learn about each other's schedules, and reschedule their transmissions, if needed. If TSCH and BLE coordinators are collocated in the same gateway, cooperative coexistence is preferable. That way, these coordinators can exchange their schedules using the connections of the gateway.

In this chapter, four different approaches are proposed to allow the cooperative coexistence of BLE and TSCH. These approaches include a time-domain, a frequency domain, and two hybrid methods. In the first solution, the channels of BLE and TSCH are separated in such a way that they do not share a common channel. In the second solution, simultaneous transmission of BLE and TSCH is avoided, by shifting the TSCH transmission in time domain. In the third solution, the hopping patterns of BLE and TSCH are separated. In the fourth solution, the active TSCH link is dynamically changed.

The next section discusses relevant, preceding research that touches upon our area of inquiry. After this, section 3.3 provides more insights into the functioning of BLE and TSCH. Section 3.4, defines the coexistence problem more clearly, and describes the proposed solutions in more depth. Section 3.5 describes the performance of each approach. Finally, Section 3.6 lists the most important findings.

3.2 Related Work

The detrimental effect of CTI on the 2.4 GHz ISM band has been widely researched, with many authors subscribing to the notion that MAC layer coexistence solutions can eliminate this effect of CTI. However, how exactly this scenario could work in practice remains unclear. To the best of our knowledge, this is the first study that proposes cooperative coexistence of collocated BLE and TSCH networks.

In [7], the effect of various 2.4 GHz radio transmissions on the TSCH link is examined, using packet reception probability as a quality metric. According to this study, the external Bluetooth and WiFi transmissions decrease the packet reception probability significantly, while the detrimental effect of this interference is dynamic over time.

In [22], the effect of CTI is minimized for TSCH networks, by using dynamic channel whitelisting. In this process, the TSCH channels are frequently sampled, in order to assess their quality, upon which reliable channels are whitelisted. During channel hopping, only whitelisted channels are allowed to choose. In this way, unreliable channels are avoided. This method is evaluated in a high interference scenario and 24% improvement in packet reception ratio is observed. In this study, sampling and whitelisting are mainly done by the coordinator. This centralized approach is further extended in [23], which proposes such sampling on each node of the network before combining these data in the coordinator. This distributed solution predicts the overall interference better than the centralized solution. However, both [22] and [23] use non-cooperative coexistence, since the interference is predicted. These methods can be used, if the interfering

network is not cooperative, otherwise cooperative coexistence methods outperform the non-cooperative methods.

There are other studies, i.e. [16] and [9], about cooperative coexistence of different communication protocols that relate to our work. In [16], two methods for time domain cooperative coexistence of BLE and IEEE 802.15.4 are proposed. In one of the methods, BLE transmissions adopt to IEEE 802.15.4 schedule, while in the other method IEEE 802.15.4 transmissions adopt to BLE schedule. That way, only one technology is active at an instant, while the other one sleeps. [9] proposes a cooperative coexistence mechanism for IEEE 802.15.3 [24] and 802.15.4 protocols. In doing so, they considered the PHY and MAC layer characteristics of both protocols. Their proposed solution, named Alternating Wireless Activity, allows IEEE 802.15.4 transmissions in IEEE 802.15.3 CTA duration and IEEE 802.15.3 transmissions in IEEE 802.15.4 inactive portion. They assume only beacon-enabled mode of IEEE 802.15.4 and exchange synchronization information between the two networks. However, both [16] and [9] do not consider the frequency domain characteristics of the networks, which, if considered, can increase the number of coexistence options.

In [25], a radio scheduler receives both time and frequency information from the connected radios. The scheduler creates a scheduling matrix based on the time and frequency intervals of the lowest prioritized technology. Using this matrix, the lowest prioritized radio avoids transmissions when there is a possible collision. This method is a good way to model the channel occupancy. Our method, therefore, also uses a scheduling matrix. However, the dimensions of our scheduling matrix are calculated based on the gcd of both technologies. Also, a lowest prioritized network, which avoids transmissions is absent. When a possible collision is calculated, our scheduler reschedules the transmissions.

3.3 Background

3.3.1 Bluetooth Low Energy

BLE is a wireless personal area network technology, which operates in two different modes: connectionless broadcasting and connection oriented periodic data exchange. This chapter, only discusses the connection-oriented mode of BLE, as the only way to provide time structured communication using duty cycles.

Time domain characteristics of BLE were already discussed in Section 2.3.1. In Figure 3.2 and Eq. 3.1, connection interval and connection event represented transmission

period and duration respectively. In this section, the same time-domain characteristics are used, but on top of that frequency domain characteristics are considered.

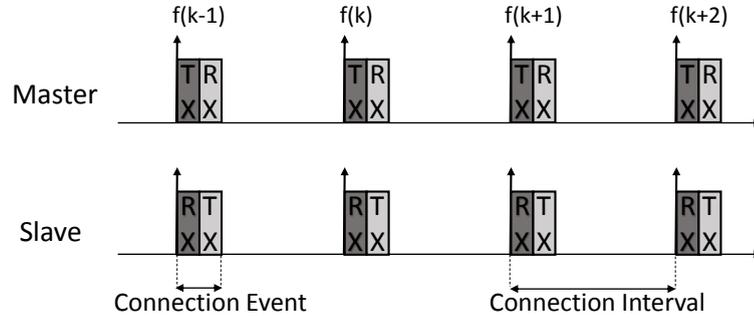


FIGURE 3.2: Time-domain structure of communications in BLE

$$\begin{aligned}
 CI &= 1.25 \text{ ms} \times K \\
 7.5 \text{ ms} &\leq CI \leq 4000 \text{ ms}, \quad K \in \mathcal{N}
 \end{aligned} \tag{3.1}$$

BLE has 40 back to back channels in the 2.4 GHz ISM band, each with 2 MHz bandwidth. Three of these channels function as advertisement channels (channel 37, 38, and 39). The rest of the channels are used as data channels (from channel 0 to 36). After each CI, BLE hops from one channel to another, by using its channel selection algorithm. This algorithm has two steps. Firstly, an unmapped channel index, CH_u , is calculated, using the CH_u calculated in the previous connection event and a predefined hop increment parameter, hop . This calculation is shown in Eq. 3.2.

$$CH_u = (CH_u + hop) \% 37 \tag{3.2}$$

If CH_u is already one of the channels given in the available channels list, it is used as the transmission channel. However, if CH_u is not in the list, it must be remapped, since the use of channels that are not in the list is prohibited. The remapping procedure takes CH_u and the number of available channels, num_{BLE} , as inputs. Then, it calculates a remapping index, ind , as shown in Eq. 3.4.

$$ind = CH_u \% num_{BLE} \tag{3.3}$$

If CH_u is not in the list, the elements of the list are ordered. Then, ind 'th element is chosen as the transmission channel.

3.3.2 TSCH

TSCH communication is divided in both time and frequency domains. In the time domain, it is divided to timeslots. From the initiation of the connection, TSCH timeslots are counted by an index, named Absolute Slot Number (ASN). In the frequency domain, TSCH transmission is divided into 16 channels. In a network, the communication of two devices with a specific channel offset is named as a link. In a link, transmission is repeated with a TSCH period. The transmission channel is calculated considering ASN , the predefined channel offset value, $offset_{CH}$, and the number of active TSCH channels, num_{TSCH} . The channel calculation formula is given in Eq. 3.4.

$$CH = List[(ASN + offset_{CH}) \% num_{TSCH}] \quad (3.4)$$

Let us suppose that there are two links in the network. The first link has 0 as channel offset (CO), while the second link has 1 as channel offset. Also, the second link has a time offset (TO) equal to one timeslot. Their TSCH period is equal to 4 timeslots. The communication patterns of these two links are given in Figure 3.3.

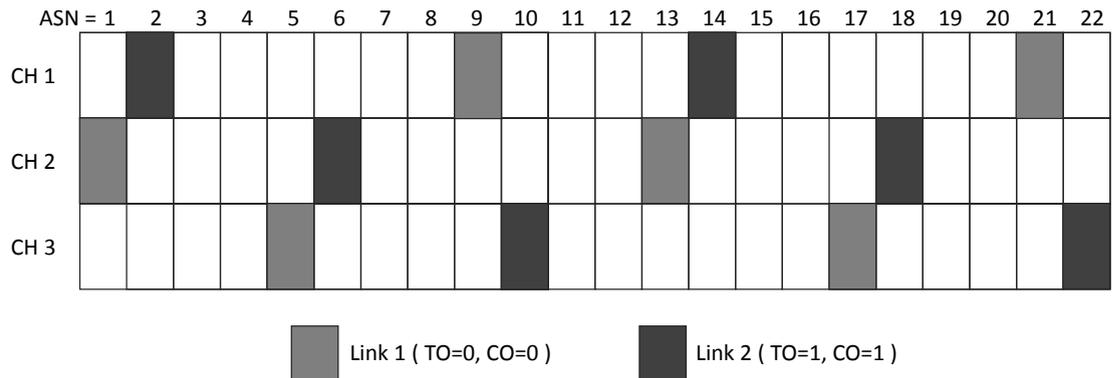


FIGURE 3.3: An example pattern of two links

3.4 Proposed Solution

3.4.1 Network Setup and Spectrum Modelling

In this section a patent of IMEC is discussed. This patent proposes a method for multi-radio coexistence. In the following sections, we propose some interference scenarios and solutions, using the idea proposed in this patent.

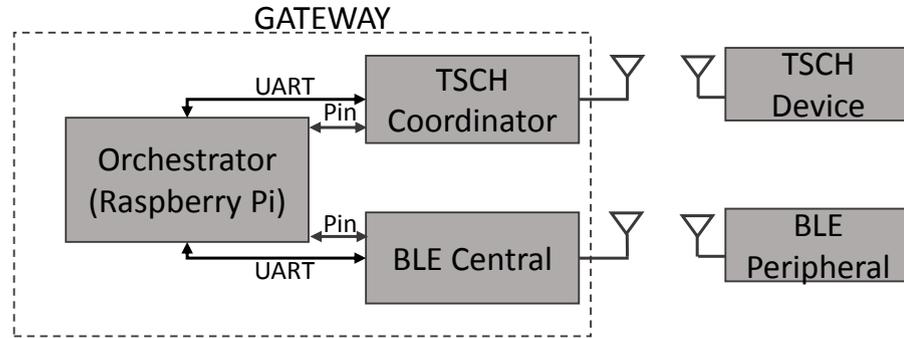


FIGURE 3.4: Network model for experiments

One of the main objectives of this patent is to provide an effective solution to mitigate coexistence problems among collocated and non-collocated radios in a wireless network. A multi-radio device and wirelessly connected end devices are presented in Figure 3.4. In this figure, the smart gateway represents a multi-radio device that includes TSCH coordinator and BLE central. The gateway further includes an orchestrator, which is arranged for scheduling the communications of BLE and TSCH. The orchestrator is a processing unit, such as a Raspberry Pi. The orchestrator receives usage information from BLE and TSCH through its connections to them and in turn produces a time and frequency dimensioned scheduling for each radio.

Based on the received communication parameters, the radio manager is able to determine a minimum time slot (T_{min}) and a minimum frequency band (F_{min}). T_{min} is derived based on greatest common divisor (gcd) of the time interval of the received communication parameters. F_{min} is derived based on gcd of the frequency channel bandwidth and frequency channel offset.

To manage the scheduled communication, the orchestrator aligns the anchor point of BLE with the beginning of the first timeslot of TSCH. Then, it creates a scheduling matrix with a unit cell and a unit width, equal to F_{min} and T_{min} . Figure 3.5 shows a scheduling matrix, that schedules the transmissions of TSCH and BLE. In this figure, P1 represents the communication of a BLE pair, and P2 represents the communication of a TSCH pair.

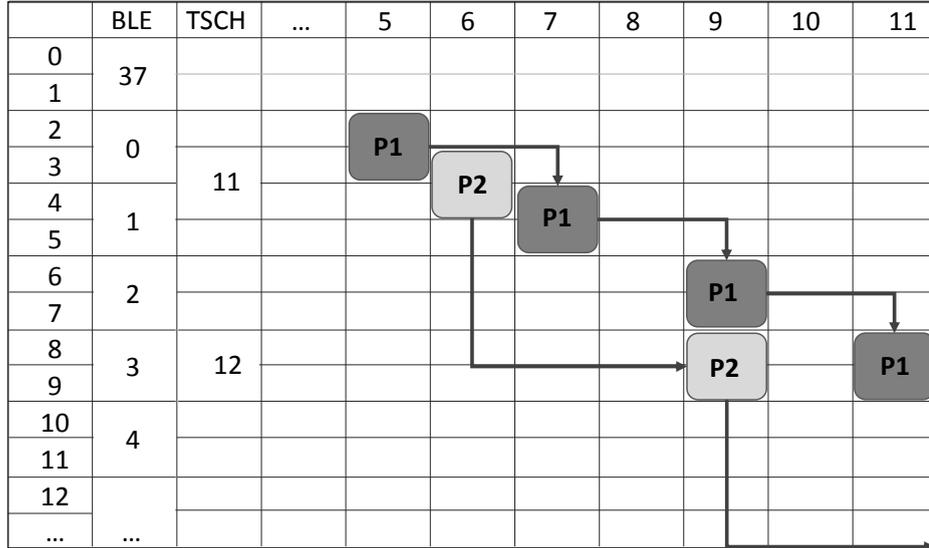


FIGURE 3.5: Scheduling Matrix

The orchestrator can be adapted to schedule the communications between collocated and non-collocated radio so that the reliability is improved. This can be achieved by scheduling the transmissions in the scheduling matrix, e.g. P1 and P2, in such a way that they rarely (ideally never) overlap. In this type of scheduling, the objective function of the scheduler is minimizing the overlaps in the scheduling matrix. Many other objective functions can also be used. Maximizing overlap to create a communication blocker or minimizing the horizontal distance between the transmissions to minimize end to end latency are two such examples. However, in this thesis, we only consider an objective function, which minimizes the overlaps in the scheduling matrix. For reasons of simplicity and to show that the idea works, we used channel constraints in our experiments. This set-up limits the available channels that can be used by BLE or TSCH.

In our experiments, we have used only one TSCH end device and one BLE peripheral. In the gateway, we have used a TSCH coordinator and a BLE controller. All these 4 devices use Texas Instruments Sensortag CC2650 as hardware. We used a Raspberry Pi device as orchestrator. The orchestrator is connected with radios using both UART and pin connections, as depicted in Fig. 3.4.

3.4.2 Considered Interference Cases and Their Solutions

We categorized the Cross Technology Interference (CTI) between BLE and TSCH into two cases.

Case 1/Static: There is a TSCH link that never interferes with BLE. Therefore, a static solution, i.e. one requiring only one update to avoid interference, suffices to decrease the PER.

Case 2/Dynamic: While none of the TSCH links show the behaviour mentioned in Case 1, there are TSCH links that occasionally do not interfere with BLE. It is possible to predict which link will collide with BLE connection event and at what time. In order to avoid this type of interference, a dynamic solution, which requires periodic monitoring and updating of the scheduled cells, is needed.

In line with our focus on the above-mentioned two scenarios, we developed four different solutions to avoid interference. Solution 1, 2, and 3 provide solutions for the static case, requiring only one link update. Solution 4 provides solutions for the dynamic case, demanding periodic link updates.

Solution 1/Frequency Division: The channels in the 2.4 GHz spectrum are separated, so that none of the TSCH channels interfere with the BLE channels. This solution is a frequency domain solution. As such, it does not consider the time domain characteristics of any of the protocols.

Solution 2/Time Division: In order to avoid interference, a specific TSCH link, which is never scheduled concurrently/simultaneously with the BLE connection event, is activated. Therefore, this link never interferes with BLE. In other words, TSCH transmissions are done in timeslots that never overlap with BLE transmissions in the time domain. Therefore, this solution is a time domain solution, and it does not consider the frequency domain characteristics of any of the protocols.

Solution 3/Pattern Division: BLE and TSCH transmissions can overlap in the time domain. However, when they overlap, they use different channels. This solution differs from the first one, since it does not limit the number of available channels for each protocol. This solution uses the division of the hopping patterns.

The time and frequency domain characteristics of static solutions are shown in Figure 3.6. For ease of reading the figure displays only 2 channels of 2.4 GHz spectrum that are commonly used by both BLE and TSCH. Furthermore, the periods of transmissions are chosen as two or three timeslots, which is very low for real scenarios.

Among the static solutions, Solution 1 requires BLE to adapt TSCH transmissions, by changing its own schedule. However, in Solution 2 and 3, TSCH adapts BLE transmissions. Therefore, in Solution 1 BLE is used as adapting network, while in Solution 2 and 3 TSCH is used as adapting network.

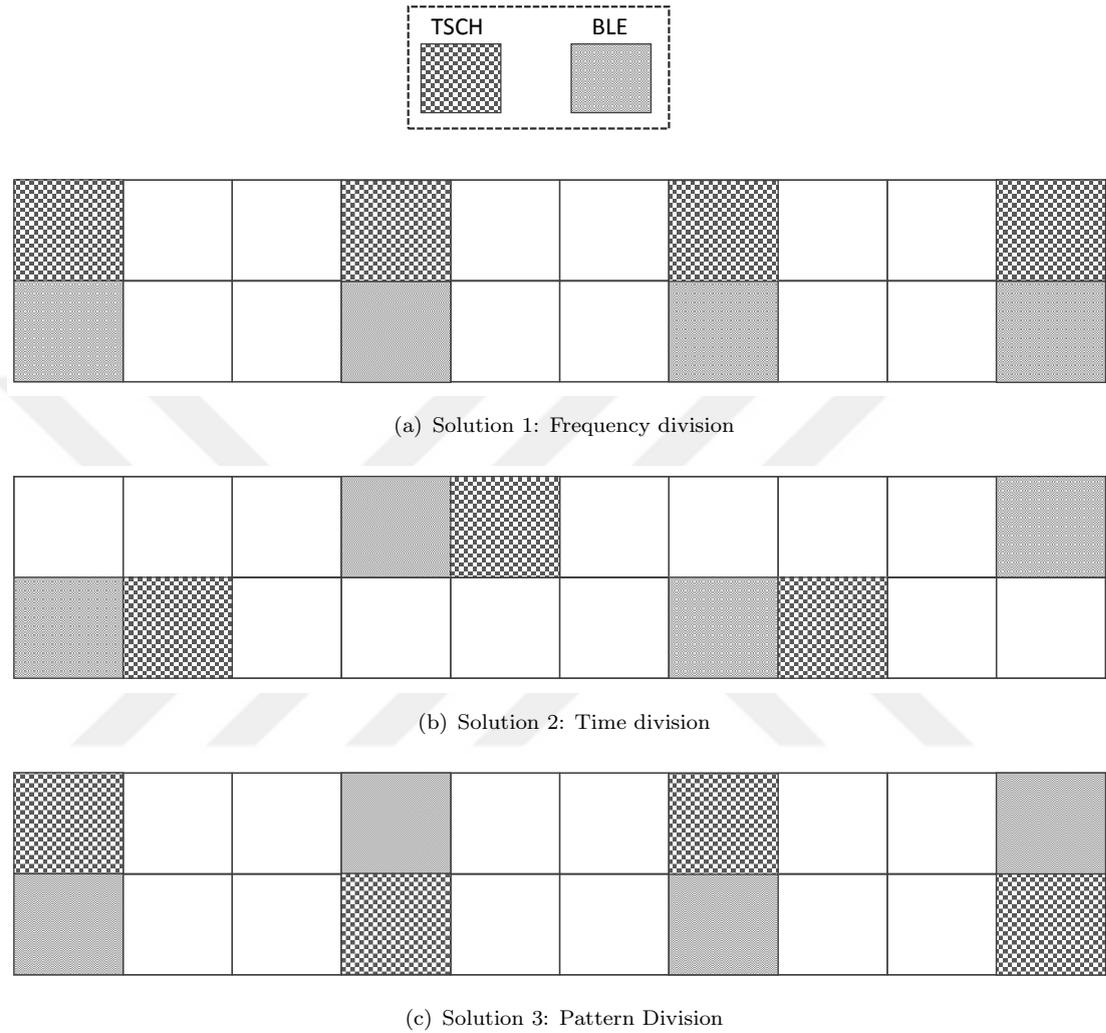


FIGURE 3.6: Static solutions for Case 1 type of CTI is given. In the figures, X axes represents time, while Y axes represents frequency.

Solution 4/Periodic Link Update: To apply this solution, at least two TSCH timeslots should be selected. Periodically, one of these timeslots should be activated and the other one should be deactivated. The activated link should provide less PER than the other one. In this solution TSCH is used as an adapting network, since the TSCH links perform the periodic updates.

An example of hopping patterns for BLE and two TSCH links are given in Figure 3.7. In this figure, the BLE period is considered as 3 timeslots, while the TSCH period is 2 timeslots. At the beginning, the dynamic scheduler activates TSCH link 1. This link is

used until timeslot 6. However, at that point, it deactivates link 1 and use link 2, since a collision is expected between BLE and TSCH link 1 on the 7th timeslot. Similarly, the scheduler switches between the links before timeslot 16, from link 2 to link 1. Prior to timeslot 19, it switches from link 1 to link 2. In this way, all of the possible collisions are avoided at the end of timeslot 22, while the single use of link 1 or link 2 causes 2 collisions.

In more complex and real life scenarios, the number of channels can be higher and there might be some constraints regarding the period of the update messages. Processing delays and response speed cause these constraints. For these reasons, we introduced an update window. The orchestrator creates matrices, which are depicted in Fig. 3.5. The length of the x axis of the matrices is named as window size. The orchestrator fills the matrices and calculates the number of expected collisions for each link, after which it chooses the link that has the lowest chance of collision. If the chosen link is not already activated, it sends an update message stating that the current link must be deactivated and the chosen link must be activated. This update message can only be sent at the beginning of an update window.

The performance of the dynamic solution relies on the available links and the update window size. If the window size is smaller than the minimum of two consecutive collisions, then this solution can achieve 0% PER. However, even in experiments with a larger window size, a significant improvement in the PER can be observed.

3.5 Performance Evaluation

3.5.1 Test Setup

A smart gateway, including a Raspberry Pi and two TI CC2650 Sensortags is connected wirelessly to the TSCH end device and the BLE peripheral. The smart gateway has one Sensortag as BLE coordinator, the other one as TSCH coordinator, while the Raspberry Pi serves as orchestrator. Similarly, one of the end devices is a TSCH device, while the other one is a BLE end device. This network is given in Fig. 3.4.

On the TSCH side, the data packets are transmitted from the end device to the gateway. Each TSCH timeslot involves the transmission of a data packet and the reception of the ACK packet. The timeslot size is 10 ms. The MAC layer retransmissions are deactivated. On the BLE side, each connection event involves the transmission of 5 packets and their ACKs.

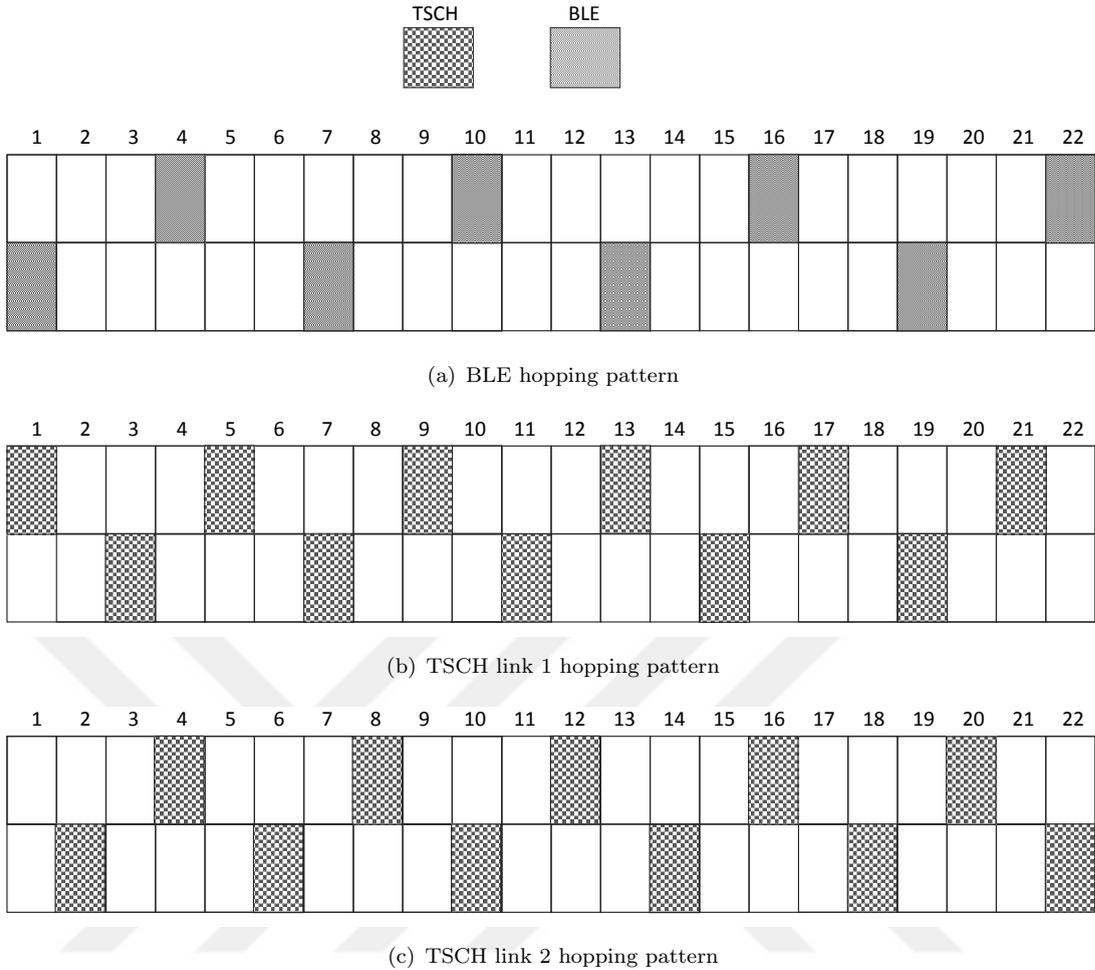


FIGURE 3.7: Hopping patterns of BLE and two links of TSCH are given. In the figures, X axes represents time, while Y axes represents frequency.

In the experiments, 1000 data packets are transmitted on the TSCH connection, and PER is measured considering the error ratio of these packets. In other words, BLE is used as interfering network and TSCH is used as affected network.

Table 3.1 shows the test parameters and the PER results.

3.5.2 Noise on PER

The PER values discussed in the experiments are measured using the data packets of TSCH. TSCH devices do not only transmit data packets, but they also periodically broadcast beacon to advertise the presence of the TSCH network. These beacon packets play a critical role in initiating and preserving the connection.

If both a beacon and a data packet are scheduled for a specific timeslot, then the beacon packet would be transmitted while the data packet is dropped. This is because the

TABLE 3.1: Test scenarios and the resultant PERs

	Case	Solution	BLE channels	TSCH channels	BLE CI	TSCH period	PER default	PER solution
Sc. 1	Static	Sol. 1	3,22 → 32,36	26,12	100	100	46.4 %	7.4 %
Sc. 2	Static	Sol. 2	3,22	26,12	100	100	46.4 %	8.1 %
Sc. 3	Static	Sol. 3	3,6,18,22	26,12	100	70	2.7 %	0.2 %
Sc. 4	Static	Sol. 3	3,22	pattern introduced	100	100	46.4 %	0.8 %
Sc. 5	Dynamic	Sol. 4	3,6,18,22	26,12	100	70	2.7 %	1.2 %
Sc. 6	Dynamic	Sol. 4	3,22	26,12	100	70	5.9 %	2.5 %
Sc. 7	Dynamic	Sol. 4	3,22	12	100	70	5.1 %	1.3 %
Sc. 8	Dynamic	Sol. 4	3,6,18,22	23,16,26,12	100	70	2.2 %	1.1 %
Sc. 9	Dynamic	Sol. 4	3,8,17,22	20,18,14,12	100	70	5.4 %	1.5 %
Sc. 10	Dynamic	Sol. 4	3,6,18,22	26,12	100	130	3.2 %	1.7 %

current 802.15.4 standard does not support simultaneous multi-channel transmission. Consequently, the transmission of beacon packets increases the PER, although it has no relation with CTI. In order to compensate for this effect, a different and prime number period is assigned as the beacon period. However, there is still a significant amount of noise on PER calculation.

In Sc. 2 and 4, the beacon packets are transmitted more frequently, because these scenarios have a high PER before the relevant solution is applied on run-time. If enough beacon packets are not transmitted, these scenarios would suffer from disconnections. In these scenarios, up to 8% of the PER is caused by beacons. In the other scenarios, beacon period is set higher and the effect of beacon noise is less than 1%.

3.5.3 Case 1 - Static Experiments

The static experiments require either hard coded schedules or only one link update during the runtime. Because in the static cases, the newly chosen link never interferes with the BLE transmissions. Three different solutions are proposed for static experiments in Section 3.4.2.

Solution 1/Frequency Division This solution proposes the separation of transmission frequencies of BLE and TSCH. This solution is tested in Sc. 1, which shows a significant improvement in PER. In this scenario, the TSCH connection suffers from CTI, because BLE and TSCH channels are not disjoint. After the rescheduling, Ch 32 and 36 are activated for BLE instead of Ch. 3 and 22. Therefore, the TSCH and BLE

channels become disjoint, which decreases the PER from 46.4% to 7.4%. As a result, a significant improvement in the PER is observed.

Solution 2/Time Division This solution proposes the separation of transmissions in the time domain, and it is tested in a set-up that reflects Sc. 2. In the default setup of this scenario, the TSCH connection has a high PER: TSCH and BLE have the same transmission period and they always transmit at the same time. Approximately half of their transmissions fail, because ch 3 of BLE and ch 12 of TSCH use the same frequency. However, when the time division solution is applied, TSCH transmissions are shifted 50 ms. In this way, the PER decreases from 46.4 % to 8.1%.

Solution 3/Pattern Division This solution provides an improvement in PER by separating the hopping patterns of BLE and TSCH. In other words, using this solution provides disjoint hopping patterns to BLE and TSCH. The main advantage of this solution compared to Solution 1 and 2 is that it does not set any limitation on time or frequency resources. This solution can be applied in two different ways by a) choosing a CTI-free pattern from given options, or b) constructing a new CTI-free pattern.

Solution 3a Firstly, Sc. 3 tests solution 3, by choosing a CTI-free pattern from given options. The orchestrator ensures through its calculations that the TSCH link, which has $TO=3$ and $FO=0$, never interferes with the BLE transmissions. Therefore, the use of this link provides a more reliable communication with $PER=0.2$ % than other links (e.g. the link, which has $TO=2$ and $FO=1$ provides $PER=2.7$ %).

Solution 3b If there is no CTI-free link available, then a new CTI-free link can be defined. Sc. 4 tests this solution. In order to create the most challenging scenario, TSCH and BLE periods are set to be equal, and the TSCH is enforced to use Ch 12 ($F_c = 2410MHz$) and Ch 20 ($F_c = 2450MHz$), that use the same frequency intervals as the interfering BLE connection (BLE uses Ch 3 ($F_c = 2410MHz$) and Ch 22 ($F_c = 2450MHz$)). Therefore, in this scenario, BLE uses one of the active channels, and TSCH needs to use the other active channel on every transmission, because both are scheduled at the same time-unit. In other words, the 10 ms time interval is fully utilized during the transmission times. Such a scenario is shown in Fig. 3.7(c). Note that in Fig. 3.7(c) both of the radios have a hopping pattern period of 2. Therefore, they repeat the same pattern after every two periods, e.g. the channels they used in $TS = i$ and $TS = i + (2 \times period)$ are the same.

Full utilization of active timeslots can be achieved by assigning the TSCH pattern the same period as the BLE pattern. The period of the BLE pattern can be calculated through the hopping algorithm given in Section 3.3.1. According to this algorithm, after every CE, BLE should hop between 37 different index numbers. Then, using the resultant index number, the algorithm remaps and calculates the next active channel. Since 37 is a prime number, the BLE hopping algorithm always has a period of 37, independently of the selection of the hopping amount and the remapping stage. Therefore, the period of the new TSCH pattern should also be 37.

For example, for Sc. 4, the list of the disjoint TSCH channels are calculated as given in the table. Firstly, the unmapped BLE channel index is calculated for each future timeslot, then they are mapped to actual BLE channels using BLE remapping. Following this, a disjoint TSCH channel, which does not overlap with the remapped BLE channel, is calculated.

TABLE 3.2: Calculation of disjoint TSCH channels for Sc. 4

Timeslot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
BLE unmapped ch. index	5	10	15	20	25	30	35	3	8	13	18	23	28	33	1	6	11	16	21
BLE remapped ch.	22	3	22	3	22	3	22	3	3	22	3	22	3	22	22	3	22	3	22
Disjoint TSCH ch.	12	20	12	20	12	20	12	20	20	12	20	12	20	12	12	20	12	20	12

Timeslot	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
BLE unmapped ch. index	26	31	36	4	9	14	19	24	29	34	2	7	12	17	2	27	32	0	5
BLE remapped ch.	3	22	3	3	22	3	22	3	22	3	3	22	3	22	22	22	3	3	22
Disjoint TSCH ch.	20	12	20	20	12	20	12	20	12	20	20	12	20	12	12	12	20	20	12

As the final step, the disjoint TSCH channel list is reconfigured, in line with the timeslot duration of TSCH. The TSCH MAC layer requires to know where to hop after every timeslot, which is ($dur_{TS} = 10ms$). However, we calculated a disjoint TSCH pattern,

to happen once in every $\text{lcm}(CI \times TSCHperiod)$ ms. A packet loss occurs only if BLE and TSCH use the same channel during these simultaneous transmissions.

In Case 2 experiments, PER depends on the number of both interfering and non-interfering channels. In Sc. 5, 6, 7, and 8, the effect of the number of non-interfering channels on PER is evaluated. For this purpose, the CI, TSCH period, and the number of interfering channels are kept constant. In other words, in these experiments, the CI and TSCH period are set at 100 and 70, respectively, and only one channel of BLE (Ch. 3) and TSCH (Ch. 12) overlaps.

The number of channels affects the PER, but only if the channels are used during simultaneous transmission times. For example, if there is a specific channel that is never used during simultaneous transmission times, activation of this channel will neither increase nor decrease the PER.

Let N_b be the number of CIs between two consecutive simultaneous transmission times. Then, using Eq. 3.7, N_b is 7 for Sc. 5, 6, 7, and 8. Then, using Eq. 3.2, simultaneous transmission times have the following channel assignment series: $\{ X\%37, (X+1*7)\%37, (X+2*7)\%37 \dots \}$ Note that 37 is a co-prime of 7. For this reason, the active BLE channels are equally distributed to the simultaneous transmission times. During the simultaneous transmission times, the chance of using a disjoint channel becomes higher. Consequently, as the number of BLE channels increases, the PER can be expected to decrease. This can be observed in Sc. 5 and 6. In Sc. 5, four BLE channels are used. When the channels are limited to two, as is the case in Sc. 6, the PER almost doubles.

$$N_b = \frac{LCM(CI \times TSCHperiod)}{CI} \quad (3.7)$$

$$N_t = \frac{LCM(CI \times TSCHperiod)}{TSCHtimeslotdur.} \quad (3.8)$$

Let N_t be the number of TSCH timeslots between two consecutive simultaneous transmission times. Then, using Eq. 3.8, N_t is 70 for Sc. 5, 6, 7, and 8. Then, using Eq. 3.3, simultaneous transmission times have the following channel assignment series: $\{ X\%ListLength, (X+1*70)\%ListLength, (X+2*70)\%ListLength \dots \}$. Unlike BLE, ListLength and 70 might not be co-prime. As a result, TSCH might hop between less channels than it can employ during simultaneous transmission times. For example, in Sc. 6 TSCH uses two channels, and simultaneous transmission occurs after each 70 TSCH timeslot. In this case, Eq. 3.3, always produces the same result. An example of this calculation is given in the Table 3.3, in which the offset value is set to 0.

TABLE 3.3: An example channel calculation for TSCH

ASN	(ASN+offset) % 2	Used channel
1	1	12
71	1	12
141	1	12
211	1	12
...		

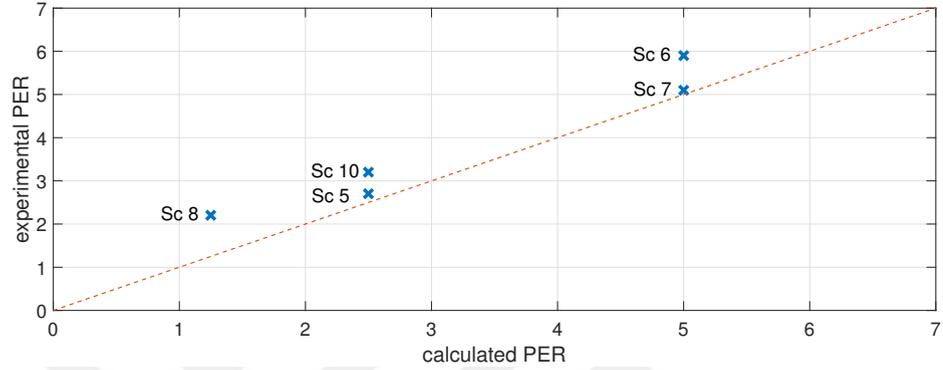


FIGURE 3.9: Calculated PER is compared with the experimental results of dynamic experiments. Ideally, all the experimental results are expected to cross the dashed line, but the noise increases the experimental PER

Considering the aforementioned characteristics of channel distribution algorithms, the PER of scenarios with only one interfering channel can be calculated using Eq. 3.9.

$$\begin{aligned}
 Ratio_{time} &= \frac{TSCH_{period}}{LCM(CI, TSCH_{period})} \\
 num_{iTSCH} &= length(TSCH_{period} \% num_{TSCH}) \\
 Ratio_{freq} &= \left(num_{BLE} \times num_{iTSCH} \right)^{-1} \\
 PER &= Ratio_{time} \times Ratio_{freq}
 \end{aligned} \tag{3.9}$$

Using the Eq. 3.9, Figure 3.9 is created. In this figure, the calculated PER values are compared with actual PER values of Sc. 5, 6, 7, 8, and 10. This figure shows that the PER calculation is accurate, but that the experimental PER can be 1% higher than the calculated one. This difference can be explained by the noise (Sec. 3.5.2) in the experiments.

Solution 4 This solution proposes the periodic change of active TSCH links. The change of active TSCH timeslots is referred to as a link update. The link update commands are created by the orchestrator of the network as is shown in Fig. 3.4.

In order to test solution 4, six different experiments have been conducted. These experiments are Sc. 5, 6, 7, 8, 9, and 10. Among these experiments, Sc. 5, 6, 7, and 8 present the effect of Solution 4, when the CI and TSCH period are 100 and 70 respectively and only one channel interferes. Sc. 9 presents the performance of Solution 4 when more channels interfere. In this scenario, all of the BLE and TSCH channels interfere with each other. Sc. 10 shows that Solution 4 works with other (CI, TSCH period) combinations as well.

The link update messages of Solution 4 introduce additional message traffic to the network. Therefore, solution 4 creates costs to the network: extra power consumption. In this sense, solution 4 is different than the static solutions, which do not create message overhead. This cost is evaluated considering the ratio of overhead messages to the total messages.

During the experiments, it was observed that the link update messages are not generated within a constant period. Instead, each time, the period of link update messages changes between a couple of possible values. This change is not probabilistic, but deterministic with a repeating sequence. For example, in Sc. 5, time difference between each link update is given in the following set: { 11.9, 11.2, 1.4, 1.4, 11.9, 11.2, 1.4, 1.4 ... } Therefore, in Sc. 5, the distribution of the link update messages is 11.9 with 25 %, 11.2 with 25 %, and 1.4 with 50 %. Using these values, the average link update period is calculated as 6.475. Table 3.4 and Figure 3.10 display the period of link update messages, based on the same deterministic method. The overhead of the link update messages is calculated as the ratio of the update messages to the total number of messages. Using Eq. 3.10, overhead results are also given in Table 3.4. Note that in the table overhead is shown as a percentage.

$$Overhead = \left(\frac{Averageupdateperiod}{TSCHperiod} + 1 \right)^{-1} \quad (3.10)$$

TABLE 3.4: The overhead created by link update messages

Scenario	PER improvement	average update period (s)	overhead (%)
Sc. 5	2.7 → 1.2	6.475	1.07
Sc. 6	5.9 → 2.5	4.32	1.59
Sc. 7	5.1 → 1.3	4.32	1.59
Sc. 8	2.2 → 1.1	25.9	0.27
Sc. 9	5.4 → 1.5	12.95	0.54
Sc. 10	3.2 → 1.7	3.44	3.64

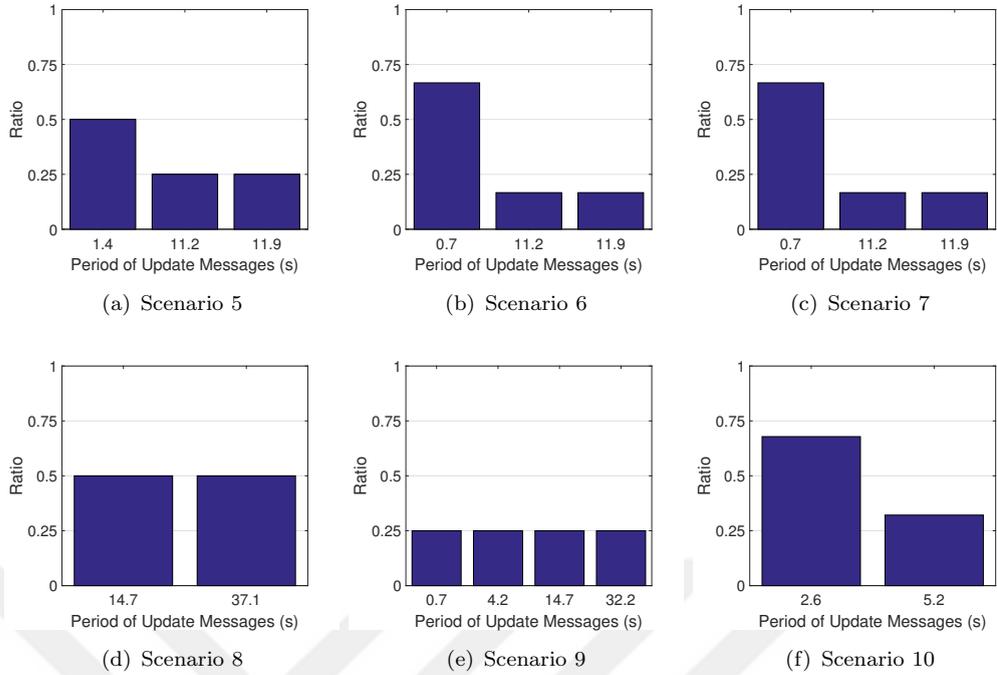


FIGURE 3.10: Link update message period for each dynamic scenario

Table 3.4 shows that PER is improved in all of the dynamic scenarios using Solution 4. However, Solution 4 did not achieve 0 % PER. There are two reasons for this. Firstly, PER can be affected by noise, which is explained in more depth in Section 3.5.2, up to 1%. Secondly, if both links collide within the length of the update window, a possible collision cannot be avoided.

From the scenarios with constant periods and one interfering channel, i.e. Sc. 5, 6, 7, 8, the effect of the number of channels on the overhead can be observed. The overhead decreases as the number of BLE channels or num_{TSCH} increases. Also, Sc. 8 and 9 show that as the ratio of interfering channels grows, so does the overhead. Lastly, in Sc. 5 and 10 an increase in (TSCH period/CI) leads to more overhead.

3.6 Conclusion

In this chapter, four cooperative coexistence solutions have been proposed. These solutions improve the reliability of cooperative and collocated TSCH and BLE networks, by minimizing PER. They use a scheduling matrix, proposed in an IMEC patent, to model the time and frequency domain occupancy of the network. Then, using a network orchestrator, they reschedule the overlapping transmissions.

The first three solutions apply frequency division, time division, and pattern division respectively. These solutions are static solutions, since they require only one rescheduling during run-time. The fourth solution is dynamic, which requires periodic link updates during runtime.

The solutions are tested using real world experiments. In addition, power consumption of the fourth solution is evaluated. In static scenarios, up to 45.6 % improvement in PER is observed, while in the dynamic scenarios it is up to 3.9 %. Also, the effect of the number of channels and the period lengths on PER are discussed.

These solutions are proposed to improve PER, however similar solutions can be applied for other objectives, such as minimizing latency or the number of retransmissions. These other objectives are left for future research.



Chapter 4

Conclusions and Future Work

4.1 Conclusions

The use of Wireless Sensor Networks is growing everyday. Some applications require heterogeneous use of WSN standards in the same location. However, if these heterogeneous WSNs do not use a proper coexistence mechanism, they can suffer from CTI.

In this thesis, cooperative coexistence mechanisms are proposed for heterogeneous WSNs. In Chapter 2, these methods are proposed for BLE-IEEE 802.15.4 networks, while in Chapter 3 BLE-TSCH networks are focused. In Chapter 2, these methods are proposed for collocated BLE and IEEE 802.15.4 networks. The proposed solutions minimize simultaneous transmissions between the networks, by smartly rescheduling the transmissions of the adapting network. In one of the proposed solutions, BLE is used as adapting network, while in the other one it is IEEE 802.15.4 network. Both of these solutions are evaluated using real hardware devices. It is concluded that IEEE 802.15.4 adaptation is more power efficient and also it improves packet reception ratio more than BLE adaptation. However, BLE adaptation can still be preferable, if the number of BLE peripherals is significantly lower than the IEEE 802.15.4 end devices. While Chapter 2 only focuses on time domain, Chapter 3 proposes both time and frequency domain solutions for collocated BLE and TSCH networks. There, a scheduling matrix is used to model the transmission time and frequency of the networks. PER is minimized, by rescheduling the overlapping transmissions in this matrix. This rescheduling is applied using four different solutions. In the first solution, a frequency domain method is used by adapting BLE network. In the second solution, a time domain shifting is applied by adapting TSCH network. In the third and fourth solutions, hybrid methods are used by adapting TSCH network. The first three solutions provide up to 45.6 % improvement in packet reception ratio, and they also do not have any energy overhead. In this sense,

they are superior than the fourth solution. However, the fourth solution is useful for the scenarios, in which link updates are allowed, but time and frequency rescheduling are not allowed. This might be the case for less flexible, densely used networks.

4.2 Recommendations for Future Research

There is still room for further investigation and research in coexistence of 2.4 GHz networks. The methods discussed in Chapter 2 and Chapter 3 can be combined to provide coexistence of three WSN standards, TSCH, BLE, and IEEE 802.15.4. In this way, the number of connected networks can be increased. WiFi can also be added among the coexisting standards, since it is a widely used 2.4 GHz standard. Furthermore, our study can be extended for non-cooperative coexistence. Some real life applications might require the network coordinators to be in separate locations. There, cooperation between the coordinators might not be possible and non-cooperative coexistence methods might be required. In addition, our solutions can be further extended for other performance objectives than minimizing PER. For example, a new solution can minimize end-to-end latency and energy efficiency of the networks. For these objectives, the use of scheduling matrix, which is discussed in Chapter 3, is highly recommended.

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