Predicting the Channel Access of Bluetooth Low Energy

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Abstract-Bluetooth Low Energy (BLE) is one of the key enablers for low-power and low-cost applications in consumer electronics and the Internet of Things. The latest features such as audio and direction finding will introduce more and more devices that rely on BLE for communication. However, like many other wireless standards, BLE relies on the unlicensed 2.4 GHz frequency band where the spectrum is already very crowded and a channel access without collisions with other devices is difficult to guarantee. For applications with high reliability requirements, it will be beneficial to actively consider channel access from other devices or standards. In this work, we present an approach to estimate the connection parameters of multiple BLE connections outside our control and knowledge by passively listening to the channel. With this, we are able to predict future channel access of these BLE connections that can be used by other wireless networks to avoid collisions. We show the applicability of our algorithm with measurements from which we are able to identify unknown BLE connections, reconstruct their specific connection parameters, and predict their future channel access.

Index Terms—Bluetooth Low Energy, Channel Access Prediction, Coexistence, Wireless Networks

I. INTRODUCTION

Due to the Internet of Things and Industry 4.0 trends in both consumer electronics and industrial applications, an increasing number of devices are wirelessly connected. Currently, most of these devices operate in the unlicensed 2.4 GHz industrial, scientific and medical (ISM) band, and each new one is an additional competitor for channel access. Since reliability is a key element in wireless communication, the capability of sensing and avoiding interference becomes essential. Popular wireless standards such as Bluetooth® Classic (BT), Bluetooth® Low Energy (BLE), Wireless Local Area Network (WLAN), and Thread include channel access methods which observe the channel before transmitting or distribute the communication over multiple channels to minimize the chance of collisions on blocked ones. Many low-power wireless sensor networks rely on deterministic channel access rather than random channel access to stay in sleep mode as long as possible. If the access to the channel is systematic, there is a good chance for other devices to identify the channel access pattern and include it in their own access scheduling. However, this systematic access might only be known to the communicating devices and may appear random to external viewers. One example is BLE, where connected devices agree on specific transmission times for the communication. For the devices themselves, the communication happens periodically, however, due to channel hopping, the channel access might appear random from an external viewpoint.

In this work, we propose an approach to identify active BLE connections, estimate connection specific parameters, and predict future channel access of these connections. The current BLE version supports two different channel access algorithms and by only passively listening to a single BLE channel, we can reconstruct both for multiple BLE connections in parallel. For the newest channel access algorithm, we will show the possibility to fully reconstruct the channel hopping pattern of a connection, including the access to channels which are not actively observed. The channel access information can be included in wireless networks with high reliability requirements to actively avoid collisions with BLE connections active in the same area. The rest of the work is organized as follows. In Section II we give an overview of the important parts of the BLE specification and how channel access is coordinated. In Section III we will introduce our approach for channel access prediction which is then evaluated in Section IV with measurements. Finally, conclusions are drawn in Section V.

A. Related Work

In the unlicensed spectrum, the coexistence with other devices has to be considered. Authors in [1], [2] studied the coexistence of different wireless communication protocols operating in the 2.4 GHz ISM band. In the case of BLE, the specification [3] defines no method to detect an occupied channel and reschedule the communication. However, BLE applies adaptive frequency hopping where specific channels can be excluded for communication. Authors in [4] studied the channel access mechanism of BLE and proposed an approach to select the best channels. Active interference mitigation is a key enabler for low power and high reliability in wireless networks. Specifically, it is important to enable deterministic channel access via estimation of communication slots available for interference-free communication. In particular, avoiding interference is a must if the ISM band is used for deterministic wireless communication, as in [5] for Time-Sensitive Networking (TSN). Authors in [6] proposed an approach to reconstruct

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BLE connection parameters which can be directly used to predict the channel access of BLE connections. This approach is similar to ours, however, their work focuses only on the older version of the channel access algorithms in BLE. Due to the needed channel hopping of the sniffer in their approach, only one BLE connection can be easily observed at a time. In our approach, only passive listening to the channel is required and both channel access algorithms of BLE are covered. The prediction for BLE advertising channels is not within the scope of this work due to its partially random nature. Authors in [7] discussed the channel access for advertisement from a jamming perspective.

B. Notation

Scalars are written as x, while vectors and matrices are denoted as lower- and uppercase boldface respectively (x and X). Vectors can be indexed with square brackets, e.g. $\mathbf{x}[r]$ is the *r*-th entry of the vector starting with index 0. Time indices are indicated with subscripts x_k .

II. BLUETOOTH LOW ENERGY LINK LAYER

BLE is a Wireless Personal Area Network (WPAN) technology that operates in the 2.4 GHz ISM band. The physical (PHY) layer is responsible for the transmission and reception of raw data. This work, however, targets the channel access prediction for BLE devices. Thus, we focus on the link layer specification of the BLE protocol. Here the channel access scheme and channel hopping are defined.

In the BLE link layer, the operational states of BLE devices are defined, which can be summarized in *connection state* and *non-connection states*. The non-connection states include all states where no direct connection between BLE devices is established. This includes the important *advertising state* where devices announce their presence and may start setting up connections. In the connection state, the devices exchange data in periodic connection events. The BLE specification [3] defines 40 channels, where channels 0-36 are used for general connection events and channels 37-39 are used for advertisement. Most of the communication in BLE is performed in the connected state, on which we will focus in the following.

A connection between *central* and *peripheral* is established through an advertisement event, where the peripheral is the one that advertises its presence and the central requests a connection. In the connection process, the necessary parameters are exchanged and the two devices start communicating. Data between central and peripheral is only exchanged during socalled connection events, which happen periodically with the connection interval c_{int} (a multiple of 1.25 ms in the range of 7.5 ms to 4 s). Each connection event includes at least one message sent by the central directly at the beginning. Afterwards, the peripheral and central transmit alternating if data is available. The peripheral is also allowed to skip connection events to save energy. To enumerate the connection events, we will use the connection event counter k, a 16bit value that always starts at zero for the first connection event, is incremented by one for every connection event, and shall be set to zero again in case of a 16-bit number overflow (65536 to 0). The goal of this work is to predict the channel access of unknown BLE connections in a certain frequency band or channel by passively listening to BLE communication in this channel. If communication between BLE devices would happen only on one channel, the access prediction would be trivial, as it occurs every c_{int} seconds in that channel. However, BLE applies frequency hopping spread spectrum (FHSS). A new communication channel is chosen for every new connection event, such that the access will appear random if only one channel is considered. This is also the reason why sniffing an already established BLE connection is a challenging task, since you need to know the connection parameters to follow the channel hopping. BLE also provides the possibility to exclude certain channels from hopping, for example if the link quality is not sufficient. The used channels are collected in ascending order in the channel map c_{map} . Table I summarizes the general connection parameters for BLE connections.

TABLE I: Connection parameters for channel hopping.

parameter	description
c_{int}	connection interval
\mathbf{c}_{map}	list of allowed channels
$n_{ m ch}$	number of allowed channels
k	connection event counter
ch_k	calculated channel for the k-th event
r_k	remapping index to account for c_{map}
ch'_k	used channel for the k-th event

In the BLE specification there are currently two channel hop algorithms defined. The first one is the Channel Selection Algorithm #1 (CSA#1), which was released with the first BLE specification, and the second is the Channel Selection Algorithm #2 (CSA#2), which was implemented with BLE version 5.0. To tackle the whole access prediction problem, we will introduce both channel selection algorithms in the following.

A. Channel Selection Algorithm #1

CSA#1 is the basic algorithm for channel selection and is used for all connections between devices where at least one device has a BLE version below 5.0. In addition to the parameters in Table I, the channel hopping in CSA#1 is defined by the hop increment h_{inc} . The parameters are known for the connected devices and used to calculate the communication channel for each connection event k.

For CSA#1 the unmapped channel ch_k for the *k*-th connection event is calculated by

$$\operatorname{ch}_{k} = \operatorname{mod}\left(\operatorname{ch}_{k-1} + h_{\operatorname{inc}}, 37\right), \qquad (1)$$

where $mod(\cdot, \cdot)$ is the modulo operation which assures that ch_k is within the allowed BLE channels. Since BLE also allows adaptive channel selection, we have to check whether the calculated channel ch_k is in the allowed channel map c_{map} . If ch_k is an allowed channel, it is also set as mapped channel ch'_k and used in the *k*-th connection event. If it is not part

of the channel map, we first have to calculate the remapping index r_k with

$$r_k = \mod\left(\operatorname{ch}_k, n_{\operatorname{ch}}\right) \,. \tag{2}$$

The modulo operation ensures that r_k is restricted to the number of allowed channels n_{ch} . Now we can map the channel to ch'_k with

$$\mathbf{ch}_{k}^{\prime} = \mathbf{c}_{\mathrm{map}}\left[r_{k}\right] \,. \tag{3}$$

The remapping is performed only if ch_k is not within the allowed channel list, otherwise no remapping is performed. For the *k*-th connection event the channel ch'_k is used for communication.

An important characteristic of CSA#1 can be drawn from (1). It has the form of a *linear congruential generator* described in [6]. The special parameter choice for this equation in the BLE specification makes the hop pattern repeat every 37 connection events. For example, if a connection event occurs on channel 22 for the k = 5-th connection, it will also happen 37 connections later at k = 42 on the same channel.

To demonstrate this and show an example pattern of the CSA#1, simulations were performed with $c_{int} = 7.5$ ms and $h_{inc} = 7$. Additionally, adaptive channel hopping is activated where we do not allow communication in the first 10 channels. Figure 1 depicts the connection event counter k and the corresponding channel for this event. The red lines every 37 connection events mark the positions where the channel access pattern repeats. In this figure, we show the results for the unmapped channel ch_k with orange plus-signs and the mapped channel ch'_k (without using channel 0-10) with blue crosses. The remappings are indicated with green arrows. We can see for both cases that the pattern repeats exactly after 37 connections.



Fig. 1: Example channel hopping for CSA#1.

B. Channel Selection Algorithm #2

In BLE version 5.0 CSA#2 was added, removing some disadvantages like the short repetition interval and the unequal distribution if channels are excluded. Additional to the parameters in Table I, the channel identifier CI is used in CSA#2 to calculate the communication channel. CI is assumed to be known since it can be easily calculated with

$$CI = AA[31:16] \oplus AA[15:0], \qquad (4)$$

where \oplus is the bitwise xor operation and AA is the 32-bit access address that is transmitted in every BLE packet. The notation AA[15:0] defines the first 16 bit of the access address and AA[31:16] the last, respectively.

In CSA#2 the channel hopping is defined by the pseudo random number prn_e_k , that is calculated by the channel identifier CI and the connection event counter k using the function composition

$$\operatorname{prm}_{e_{k}} = (\bigoplus_{|CI} \circ f_{\operatorname{MAM}|CI} \circ g_{\operatorname{perm}} \circ f_{\operatorname{MAM}|CI} \circ g_{\operatorname{perm}} \circ f_{\operatorname{MAM}|CI} \circ g_{\operatorname{perm}} \circ \oplus_{|CI})(k) .$$
(5)

 $\oplus_{|CI}(x)$ is a bitwise xor function conditioned on CI that can be written as

$$\oplus_{|\mathbf{CI}|}(x) = x \oplus \mathbf{CI}.$$
 (6)

 g_{perm} is a permutation operation that consists of separately bitreversing the lower and upper 8 input bits [3].

 $f_{\text{MAM}|\text{CI}}(x)$ is a multiply, add, and modulo (MAM) element, again conditioned on CI, that is defined by

$$f_{\text{MAM}|\text{CI}}(x) = \text{mod}\left(17x + \text{CI}, 2^{16}\right)$$
 (7)

The unmapped channel ch_k is now calculated using (5) for every connection event k as

$$ch_k = mod \left(prn_e_k, 37 \right) . \tag{8}$$

Compared to before, ch_k does not depend on the previous result k-1, but only on current k and CI. Similar to CSA#1, if ch_k is not part of the channel map c_{map} we first have to calculate the remapping index r_k using

$$r_k = \left\lfloor \frac{n_{\rm ch} \, {\rm prn}_{\rm e}_k}{2^{16}} \right\rfloor \,, \tag{9}$$

where $\lfloor \cdot \rfloor$ is the floor function (the greatest integer less than or equal to the argument). Now we can map the channel to ch'_k with

$$\mathbf{ch}_{k}^{\prime} = \mathbf{c}_{\mathrm{map}}\left[r_{k}\right] \,. \tag{10}$$

Remapping is performed only if ch_k is not within the allowed channel list. For the *k*-th connection event the channel ch'_k is used for the communication.

Also for CSA#2 simulations were performed with $c_{int} = 7.5 \text{ ms}$ and a c_{map} that excludes the first 10 channels. As access address we use $0 \times B0A1 CD9D$ to calculate CI by (4) and start for k = 0. Figure 2 depicts the connection event counter k and the corresponding channel for this event. The results for the unmapped channel ch_k are marked with orange plus-signs and the mapped channel ch'_k with blue crosses. Again, the remapping is indicated with green arrows. Since the repetition interval of the pattern is much larger (65536 instead of 37 connection events), no repetition is visible here. Compared to CSA#1, the remapping in Fig. 2 is not always to the same channel, it is uniformly distributed across all n_{ch} channels [4].



Fig. 2: Example channel hopping for CSA#2.

III. CHANNEL ACCESS PREDICTION

In this section, we present an approach to predict the channel access of BLE devices for both channel selection algorithms. Current approaches in literature require additional channel hopping of the sniffer, which restricts the evaluation to only one BLE connection at a time. With our approach, we are able to evaluate multiple BLE connections in parallel.

If one BLE channel is sniffed, packets of multiple connections can be observed. However, these packets can be easily separated by the access address which is transmitted at the start of each packet [3]. The header of a BLE payload is not encrypted [8], which allows us to explicitly filter the central node messages that are transmitted at the beginning of all connection events. We define the channel we are passively listening to as ch^{sniff}. In the following, the reconstruction is only described for a single device of a BLE connection (e.g. central), however, it works also for multiple devices in parallel since they can be distinguished by the access address and header. By listening passively to ch^{sniff}, the only measurement that is available is the time $\mathbf{t}_a \in \mathbb{R}^{N_a}$ of the message reception, where N_a is the number of measurements we collected as

$$\mathbf{t}_a = [t_0, t_1, t_2, \dots, t_{N_a - 1}] \,. \tag{11}$$

One important characteristic of t_a is that between measurements there is always an integer multiple of the connection interval, which can be written as

$$\mathbf{\Delta t}_{a} = \left[\underbrace{t_{1} - t_{0}}_{x_{1}c_{\text{int}}}, \underbrace{t_{2} - t_{1}}_{x_{2}c_{\text{int}}}, \underbrace{t_{3} - t_{2}}_{x_{3}c_{\text{int}}}, \ldots\right] \equiv \mathbf{x} c_{\text{int}}, \qquad (12)$$

where x_i is an integer number that may vary for each entry and c_{int} is the connection interval that we need to estimate. In our approach we use t_a to reconstruct all needed parameters for the channel access prediction.

However, we first need to reconstruct the connection interval c_{int} and determine which of the two channel selection algorithms is used. For this we have to distinguish three different cases. First, if all entries in (12) are the same, CSA#1 was used and we can estimate c_{int} by simply dividing the entries by 37, which is the repetition interval. In the second case, the entries are different, but they repeat after a few measurements. This is due to the short repetition interval of CSA#1 which

can be seen in Fig. 1 by observing channel 10. Here we have two observations per repetition interval because of the remapping from channel 0. In this example we would measure $\Delta t_a = [25c_{int}, 12c_{int}, 25c_{int}, 12c_{int}, ...]$, were we clearly see the characteristic of CSA#1. Since there is always an integer number of connection events between the measurements, c_{int} can be estimated by

$$\hat{c}_{\rm int} = \operatorname{GCD}(\Delta \mathbf{t}_a), \qquad (13)$$

where GCD is a function that calculates the greatest common divider. In the third case, (12) does not show any repetition, so CSA#2 was used. Here, c_{int} can also be calculated with (13). To account for measurement errors, a rounding to 1.25 ms steps can be applied, which is the resolution of c_{int} defined in the BLE specification [3]. For both algorithms, we give now an approach to predict the future channel access.

A. Channel Selection Algorithm #1

As mentioned in Section II-A, the channel access pattern repeats every 37 connection events. For example, if we listen to ch^{sniff} and observe packets from a device at the connection event k = 2 and k = 4, the channel access will also be observable for k = 39 and k = 41. As a result, for CSA#1 we only need the connection interval c_{int} and measure for a period of $37 c_{int}$. Every access from the device to the sniffed channel within this period will appear again after 37 connection events, the starting point is not important.

With c_{int} and the observations per repetition, the future channel access can be predicted by simply adding $37 c_{\text{int}}$ to the current observation. To account for measurement errors and clock drifts, a Kalman filter [9] with a constant velocity motion model can be used to stay synchronized with the connection interval. By listening only passively to one channel, it is not possible to estimate the channel map c_{map} and the hop increment h_{inc} . If ch^{sniff} is changed during the sniffing procedure, it is possible to estimate h_{inc} and c_{map} as described in [6]. However, since our use case is the prediction of channel access for one channel, these parameters are not needed.

B. Channel Selection Algorithm #2

Since the CSA#2 has a more complex structure and lacks the short repetition interval, all parameters listed in Table I have to be estimated for the access prediction. For the estimation, we propose a two-step approach in which we first reconstruct the connection event counter k and then the channel map c_{map} .

1) Reconstruct the connection event counter: With c_{int} computed by (13), we know how many channel hops happened between the measured connection events in \mathbf{t}_a . The sniffed BLE connection has most likely not just started, thus the connection event counter k will be some number between 0 and 65535. We define k_{init} as the connection event corresponding to the first observation of the BLE connection. i.e. the value of k for $\mathbf{t}_a[0]$. With k_{init} we can determine the value of k for all measurements in \mathbf{t}_a and also for all future measurements. For this, we construct the binary vector $\mathbf{c}^{meas} \in \{0,1\}^{N_m}$ using $\Delta \mathbf{t}_a$ as

$$\mathbf{c}^{\text{meas}} = \begin{bmatrix} \mathbf{I}_{1 \times x_1}, \mathbf{I}_{1 \times x_2}, \dots, \mathbf{I}_{1 \times x_{N_a - 1}} \end{bmatrix}, \quad (14)$$

where x_i can be calculated with c_{int} from (12) and $\mathbf{I}_{M \times N}$ is a $M \times N$ matrix where the entries are given as

$$I_{n,m} = \begin{cases} 1 & m = n \\ 0 & \text{otherwise} \end{cases}$$
(15)

 \mathbf{c}^{meas} basically lists all N_m connection events that happen during the measurement, where the entries are 1 if there was a observation in $\mathbf{c}^{\text{sniff}}$ and 0 otherwise. Additionally, we construct the binary vector $\mathbf{c}^{\text{ref}} \in \{0, 1\}^{65536}$ for all possible $k \in [0, 65535]$

$$\mathbf{c}^{\text{ref}}[k] = \begin{cases} 1, & \text{if } ch_k = ch^{\text{sniff}} \\ 0, & \text{otherwise} \end{cases},$$
(16)

using (5) and (8) to calculate all possible ch_k . Here, the unmapped channel number is used, since we have no prior knowledge of c_{map} . The idea now is to find the position where c^{ref} and c^{meas} have the highest correlation. For this, we calculate the circular cross-correlation between both and estimate the maximum as

$$r[k] = \sum_{m=0}^{N_m - 1} \mathbf{c}^{\text{ref}} \left[\mod \left(m + k, 2^{16} \right) \right] \mathbf{c}^{\text{meas}}[m] \,, \qquad (17)$$

$$k_{\text{init}} = \arg\max_{k} \left(r[k] \right). \tag{18}$$

However, to predict all channel accesses of a BLE connection, we also need to consider the remapping in (9) and (10). Therefore, c_{map} also needs to be estimated.

2) Estimate the channel map: One advantage of CSA#2 is that, compared to CSA#1, the remapping of a certain channel appears not always to the same other channel (compare the remapping in Fig. 1 and Fig. 2). Due to this, an unused channel will always be mapped to the sniffed channel ch^{sniff} if we observe the channel long enough. This characteristic can be used to completely reconstruct the channel map without listening to all channels. The schematic of this approach is shown in Fig. 3 where we assume that we are passively listening at $ch^{sniff} = 22$. Here we again use c^{ref} for all possible k and compare it with \mathbf{c}^{meas} . The two vectors are now aligned at k_{init} , as highlighted in the figure. For all entries where the unmapped channel ch_k is ch^{sniff} , both c^{ref} and c^{meas} have 1 as entry. In the cases where the calculated channel is not the sniffed one, we have no observations in general. However, in some cases we will have an observation in c^{meas} but not in c^{ref} . This is caused by remapping, for example in Fig. 3 for channel 5 highlighted with the green dashed rectangle. In this case, we can be sure that the corresponding channel, e.g. here channel 5, is not part of the channel map. However, the counterargument cannot be used. If we have no measurement we do not know if the channel access happens at the planed channel or was remapped to a channel we are not observing. With this approach, c_{map} and n_{ch} can be reconstructed iteratively.

To compute the expected number of required measurements for reconstructing CSA#2, we assume an uniform distribution both for the mapping and remapping [4]. Thus, we expect an excluded channel to be remapped to the sniffed channel on average on the n_{ch} th access. The *coupon collector problem*



Fig. 3: Process to reconstruct the channel map c_{map} .

[10] gives us an estimate for the expected number of channel access needed to access every remapped channel at least once. Combined with the probability of accessing an excluded channel $p_{rem} = \frac{37-n_{\rm ch}}{37}$, we estimate the number of channel hops to be measured to be $N_m = n_{\rm ch}(37-n_{\rm ch}) \left(\sum_{i=1}^{37-n_{\rm ch}} \frac{1}{i}\right) p_{rem}^{-1}$, with the worst case occurring for $n_{ch} = 28$, resulting in $N_m \approx 2932$, or 21.99 s for $c_{\rm int} = 7.5$ ms.

With CI, k, c_{map} , and n_{ch} we have now all parameter to perform the same hop calculation as the BLE devices of the sniffed communication. As a result, we are able to predict the access to all used BLE channels and not only the sniffed one. This is unique for this algorithm, since for CSA#1 we would need to sniff multiple channels for this. Similarly to CSA#1, it is necessary to account for clock drifts and stay synchronized with the connection interval for the prediction step.

IV. MEASUREMENT RESULTS

With our approach the channel hopping can be predicted exactly and prediction problems can only occur due to measurement errors. Therefore, instead of simulations, we directly show the applicability of our approach with measurements. Our measurement setup consists of six Nordic NRF52840 BLE devices that form three BLE connection pairs and one sniffer based on the Ubertooth One. The BLE devices are running the heart-rate monitor sample of the Zephyr Project [11], modified to allow configuring c_{int} and c_{map} . The Ubertooth One demodulates the raw signals of one BLE channel and provides the measured bitstream. With this we can measure multiple BLE connections in parallel and separate individual ones by their access address. The measurements conducted during this work are published as open-source in [12], where also a more detailed description of the setup is provided. For the following evaluation, the measurement set dataset_ubertooth/set_1 in [12] was used. The configuration of the BLE devices is listed in Table II.

TABLE II: Configuration parameters and prediction results.

CSA	c _{int} [ms]	$\mathbf{c}_{\mathrm{map}}$	\hat{c}_{int} [ms]	RSME [mus]
1	18.75	0x1FFFFFFC00	18.747	0.1163
2	12.50	0x1E00E00700	12.498	0.0699
2	7.50	0x1FFFFFFC00	7.499	0.1187

For two BLE connection pairs CSA#2 and for one the older CSA#1 was used. The devices communicated with three different values of c_{int} and we applied two different values of c_{map} . Table II provides the hexadecimal representation of

the channel maps, where 0x1FFFFFC00 corresponds to a channel map where we do not use the first 10 BLE channels (as in Figs. 1 and 2) and 0x1E00E00700 uses channels between the widely used WLAN channels 1, 6 and 11. For the sniffer, we choose a center frequency of 2.45 GHz, which corresponds to BLE channel 22.

The measurement duration was 400 s, where we used the first 100s to estimate all needed parameters as described in Section III and performed predictions on the remaining 300 s. For the prediction, we first evaluated the connection counter k of the latest measurement and then calculated the future connection events for the observed channel using the method described in Section III. To predict the access time a few connection events ahead, a simple multiplication with \hat{c}_{int} is sufficient to accurately predict the channel access. However, to account for clock drift and measurement errors, we added a Kalman filter with a constant velocity motion model to stay synchronized and predict the channel access time with a higher accuracy. Table II lists the root mean squared error (RMSE) between the measured t_a and the predicted one for the remaining 300 s, and also the estimated \hat{c}_{int} . The estimated connection intervals match the configured but are slightly lower due to clock differences between sniffer and BLE devices. For all active BLE connections, we were able to reconstruct the hopping pattern and stay synchronized to the individual connections. We could achieve an average RMSE of 0.1016 ms for the access time prediction. Fig. 4 shows the empirical Complementary Cumulative Distribution Function (eCCDF) of the absolute error between the estimated channel access and the measured one, where we additionally marked the 5% and 50% probability including the corresponding absolute error. We can see that 50% of the estimation shows an error below 0.023 ms, while only for 5% of the measurements the error exceeded 0.236 ms. With this accuracy, it is easily possible to stay synchronized and continuously perform predictions of the channel access. Since the channel access is deterministic and as soon as the corresponding parameters are reconstructed, the channel access can be theoretically estimated exactly. The presented error is due to the measurement accuracy and missing measurements.



Fig. 4: eCCDF of the absolute error between all combined measurements and the corresponding predictions.

As long as the parameters of the observed connections do not change, e.g. an update of c_{int} or c_{map} , we are able to calculate the channel hopping in a similar way as the BLE devices and continue predicting the channel access. To account for changes in the parameters, the corresponding steps in Section III have to be repeated. However, since the procedure is iterative, it is beneficial to perform the parameter estimation continuously for new measurements. This allows to detect changes and immediately update the algorithm.

V. CONCLUSION

In order to have a more deterministic channel access in ISM bands, we presented an approach to predict the channel access of multiple unknown BLE connections. We are able to identify active BLE connections and reconstruct their relevant connection parameters. Based on the standardized access schemes for BLE we are thus able to predict future channel access for multiple devices in parallel. These predictions can be used by wireless networks with high reliability requirements operating in close proximity to the BLE devices to reschedule their own communication and avoid using time slots and channels with predicted interference. For the latest channel selection algorithm in BLE version 5.0 and above, our algorithm allows to completely reconstruct the connection parameters. This gives us the unique possibility to predict the future channel access for all used BLE channels while only listening passively to a single one. The applicability of this approach is demonstrated by measurements and identification of three BLE links including their channel access.

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