On the Suitability of Bluetooth 5 for the Internet of Things: Performance and Scalability Analysis

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***Abstract*—The challenges related to the large-scale deployment of the Internet of Things to enable a wide range of application use cases have received significant attention. A number of communication technologies have been and are still developed ranging from evolved existing technologies such as 4G, WiFi or WPAN technologies to the much hyped 5G networks. Against the background of the on-going discussion on the most suitable technologies the Bluetooth Special Interest Group has proposed the next generation Bluetooth 5 specification and claims to be ready for the Internet of Things as well: mainly by increasing the maximum communication range and adapting the corresponding data rates. In this context, this paper evaluates the suitability of Bluetooth 5 for realistic application activity levels and interference scenarios, based on analytical models and validated by frequency hopping algorithm simulations. The performance results demonstrate that Bluetooth 5 is a valid technology candidate for implementation of Internet of Things applications, provided that activity level, expected coverage areas and the interference situation within the ISM band are carefully considered in the deployment process.**

I. Introduction

In the past years the Internet of Things (IoT) has experienced significant growth in the number of deployments, connecting machines, smart objects and sensors. IoT use cases are extensively discussed by industry, research as well as governments covering a wide range of application areas, such as private and commercial, industrial and logistic or public sectors. According to related varying requirements a lot of specific enabling communication technologies need to be considered [1]. In this context, Bluetooth Low Energy (BLE), widely spread in consumer hardware, is a key enabler to efficiently connect smartphones with low power sensors [2] in the coverage area of Personal Area Networks (PAN). For IoT use cases that require a higher communication range the Bluetooth Special Interest Group (SIG) provides the next generation Bluetooth 5 specification (BT5), which promises increased ranges, speed and broadcast messaging capacity [3]. Especially the improved communication range increases the relevance of Bluetooth for IoT purposes significantly, which is now additionally covering Smart Factory (industrial), Smart Home and Smart Building, as well as partly Smart Grid and Smart City use cases (see Figure 1). In this connection, this paper presents a performance and scalability analysis of BT5 systems with regard to typical IoT activity scenarios. For this purpose, a technical discussion of BT5 improvements is given in Section III. Section IV introduces two models providing performance and scalability evaluation capabilities as fundamental basis for the performance analysis in Section V. Based on a scalability analysis, this paper ends with considerations on network planning issues of BT5 networks for IoT purposes. Finally, major findings are summarized including an outlook on further work.

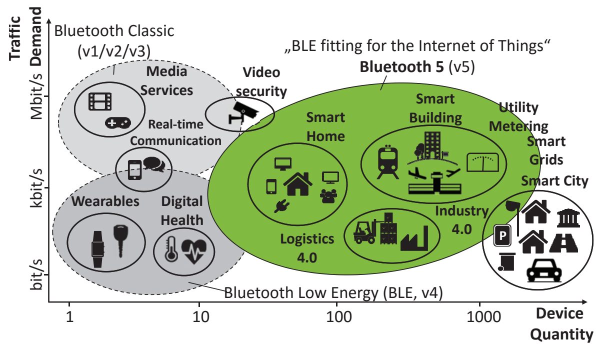

Fig. 1: Expansion of Bluetooth for the Internet of Things

II. Related Work

First discussions about the applicability of Bluetooth as a competitive candidate among available low power communication technologies in the context of IoT have been conducted for previous BLE versions [4]. Furthermore, authors illustrated potential challenges for BLE, such as mesh capabilities, broadcast

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and range improvements, that are now updated and improved within the BT5 specification. According to previous BLE versions (4.x), an analytical model of BLE throughput as a function of Bit Error Rate (BER) is presented in [5]. This model accurately predicts the maximum BLE throughput for relevant BERs and various connection intervals (connInterval). The authors in [6] introduce a simulation of BLE's Adaptive Frequency Hopping (AFH) channel algorithm. A pseudo-code for simulation software to calculate selection probability for each data channel is detailed. Related results demonstrate the collision probability between multiple BLE piconets (pairs). In [7] the same authors present an analytical model to find the selection probability of each of the 37 BLE data channels and detect the collision probability between collocated BLE piconets. In contrast, this paper presents an analytical model to detect collision probabilities of BT5 specification, which are validated by an AFH simulation model. Hence, the maximum capacity of collocated BLE piconets is derived within a scalability analysis study.

III. Bluetooth 5 Overview

The Bluetooth 5 specification [8] is published as the latest version of Bluetooth core specification in the end of 2016. It is an advancement of the latest BLE version 4.2 and improves data rate, range, broadcast capabilities, as well as fast and seamless pairing processes, affording even more flexible and versatile deployments. The new physical layer mode *LE 2M PHY* allows to operate at 2 MSymbols/s and thus enables higher data rates compared to the well known uncoded *LE 1M PHY* of Bluetooth 4. On the other hand, to achieve higher transmission ranges, a PHY mode with convolutional FEC coding is added to the specification (*LE Coded PHY*). The convolutional code is available with a coding rate of 1/2 (S=2) or 1/8 (S=8). Despite the uncoded LE 1M PHY, all improvements are optional and can be implemented based on the considered application requirements. The presented work is analyzing the capabilities of BT5 for IoT purposes and thus focuses on the LE Coded PHY modes, as key enabler for a wide range of IoT use cases.

A. Theoretical Throughput of Bluetooth 5

The transmission time strongly depends on the chosen PHY mode. The well known LE 1M PHY of Bluetooth 4 uses a 1 Byte preamble, the overall data frame is sent with 1 Mbit/s physical data rate. In contrast, the LE 2M PHY utilizes 2 Mbit/s physical data rate and has a preamble size of 2 Byte. Both coded PHY Modes consider the 1 Mbit/s physical data rate of the LE 1M PHY, but implement a FEC code rate of 1/2 or 1/8, resulting in a reduced PHY rate of 500 kbit/s respectively 125 kbit/s. The corresponding packet formats of the coded and uncoded PHY modes are introduced in Figure 2. In the following, this section considers the underlying MAC layer overhead and calculates a MAC data rate, which is a better indicator of the prospective goodput.

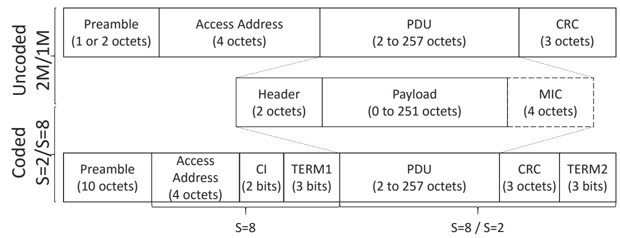

Fig. 2: Bluetooth 5 MAC frame format for data channel

Each packet is acknowledged with an empty data channel packet. The Inter Frame Space (T_{IFS}) between two packets (user data or ACK) is 150 μs, resulting in Equation 1 for the transmission time of one packet T_{Trans}.

$$T_{Trans} = T_{Packet} + 2 \cdot T_{IFS} + T_{ACK} \tag{1}$$

The detailed communication time needed for one data frame transmission is linked to the packet formats shown in Figure 2. The packet transmission time for uncoded PHY modes is depicted by Equation 2, while the transmission time for LE Coded PHY modes is represented by Equation 3.

$$\begin{aligned} T_{Packet-Uncoded} =& T_{Preamble} + T_{AccessAddress} \\ & + T_{PDU} + T_{CRC} \end{aligned} \tag{2}$$

$$\begin{aligned} T_{Packet-Coded} =& T_{Preamble} + T_{AccessAddress} \\ & + T_{CI} + T_{TERM1} + T_{PDU} \\ & + T_{CRC} + T_{TERM2} \end{aligned} \tag{3}$$

Thus, the protocol overhead (MAC) is defined as follows:

$$T_{Overhead} = T_{Trans} - T_{PDU} \tag{4}$$

As above illustrated in Figure 2, LE Coded PHY consists of a Preamble field, followed by Access Address, Coding Indicator and TERM1 field, all coded with a physical data rate of 125 kbit/s. The corresponding payload (PDU, CRC, TERM1 fields) are either coded with a physical data rate of 125 kbit/s or 500 kbit/s, depending on the chosen coded PHY mode. To calculate an accurate user data throughput, the connection intervals of BLE need to be taken into account. The connection intervals range from 7.5 ms to 4 s in multiples of 1.25 ms and define the time between two frequency hops. In one connection interval a discrete number of packets can be sent. In case of a packet error, the corresponding stations back off until the next connection interval continues communication with the next hopping frequency[8]. Thus, this work focuses on the minimum connection interval of 7.5 ms, in order to achieve a maximum throughput in case of transmission errors. The resulting goodput can be further optimized by reducing the payload size (PDU_{opt}) in order to benefit from the best case connection interval utilization, due to reduced idle times (see Figure 3).

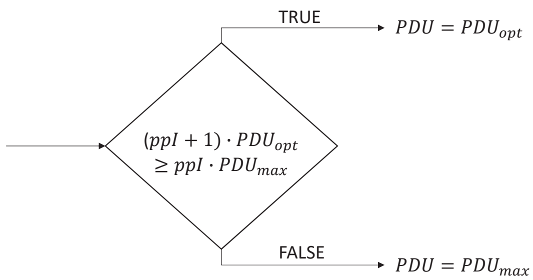

Fig. 3: Decision Algorithm for PDU size optimization

In this connection, PDU_{opt} is a function of packets per Interval (ppI), whereby ppI is the connection Interval divided by T_{packet}.

$$PDU_{opt}[Byte] = \lfloor (\frac{connInterval}{ppI+1} - T_{Overhead}) \cdot PHYRate \rfloor \quad (5)$$

Summarizing these considerations, the MAC layer goodput is calculated as presented in Equation 6. Derived results are shown in Table I.

$$Goodput = \frac{Payload \cdot ppI}{connInterval} \quad (6)$$

TABLE I: Maximum Bluetooth 5 Goodput (for a connection interval of 7.5ms)

PHY Mode	**Payload Size [Byte]**	T_{Trans} $[ms]$	**ppI**	***Goodput*** $[\frac{kBit}{s}]$
2M	215	1.248	6	1376.000
1M	251	2.468	3	803.200
Coded S=2	157	3.736	2	334.933
Coded S=8	90	7.5	1	96.000

B. Theoretical Range of Bluetooth 5

As mentioned above, the LE Coded PHYs are used to achieve higher transmission ranges due to a more robust transmission. This increased robustness leads to better receiver sensitivities which are shown in Table II. It should be mentioned that the listed receiver sensitivities are documented in BT5 specification, however, in practice many devices show much better performance. For example, receiver sensitivity for Texas Instruments CC2640R2F chipset is up to -97 dBm. Nevertheless, this work is focusing on sensitivity values listed in Table II.

TABLE II: Bluetooth 5 Receiver Sensitivities [8]

PHY mode	**Sensitivity [dbm]**
LE Uncoded PHYs	≤ -70
LE Coded PHY (S=2)	≤ -75
LE Coded PHY (S=8)	≤ -82

BT5 introduces an additional transmission power class of 20 dBm in order to further increase the maximum communication range (see Table III).

TABLE III: Bluetooth 5 Transmission Power Classes [8]

Power Class	**Maximum Tx Power [dbm]**	**Minimum Tx Power[dbm]**
1	+20	+10
1.5	+10	-20
2	+4	-20
3	0	-20

Concluding, Figure 4 summarizes the achievable data rates and related communication distances calculated based on a simple free space channel model, as well as all above introduced transmission power classes. The results are derived from a link budget consideration shown in equation 7, where L_{free} denotes the allowed free space loss, P_E the receiver sensitivity given in Table II, and P_S the transmission power given in Table III.

$$L_{free} = P_E - P_S \quad (7)$$

The maximum communication range r can be derived from the free space loss with a frequency of 2.4 GHz (Equation 8).

$$r = 10^{\frac{L_{free}}{20} - \log_{10}(\frac{4\pi f}{c})} \quad (8)$$

The LE 2M PHY mode utilizes the same sensitivity as the LE 1M PHY. However the achieved communication range is about 80% smaller compared to the LE 1M PHY [9]. This can be explained by a higher inter symbol interference caused by a higher symbol rate of the LE 2M PHY. All in all the communication distances in Figure 4 vary from 30 m to 120 m minimal communication distances (power class 3) up to 300 m to 1200 m (power class 1). Beyond, the LE Coded PHYs result in significantly higher communication distances and enable a feasible range that can be used for various IoT use cases as discussed later.

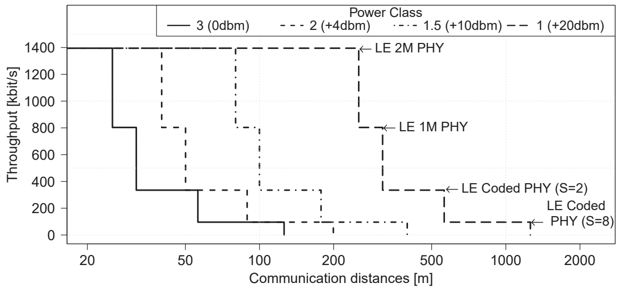

Fig. 4: Bluetooth 5 Ranges for different PHY Modes

IV. Methodical Approach for Performance and Scalability Analysis of Bluetooth 5

BT5 is operated in the 2.4 GHz ISM Band and divides the overall bandwidth in 40 channels of 2 MHz bandwidth per each frequency channel (compare Figure 5). Furthermore, Bluetooth and also BT5 implement the AFH channel algorithm, which means in the presence of interference signals BT5 will detect such interferer and skip the interfered frequencies. In this work, four different interference scenarios are considered within the following performance analysis. As depicted in Figure 5 the interference is implemented by collocated WiFi channels and reduced utilizable bandwidth S_{BT} for BT5 systems from 100% to 25%. WiFi traffic is assumed as continuous channel occupation and not as more realistic burst traffic, which covers a pessimistic worst case, but guaranteeing that the AFH detects WiFi channel occupation in advance.

The subsequent analysis approaches rely on the following assumptions. A path loss model is not considered, which results in an assumed packet loss for every hopping collision. Furthermore, it is assumed that in case of a packet error within one connInterval all packets belonging to this interval are lost. This assumption covers the worst case scenario, whereby always the first packet is interfered and communication processes are continued with the following connInverval. Analysis approaches focus on data channel communication within the BT5 connection state, whereby connection set up procedures are taken into account.

A. Analytical model for Worst Case Collision Probability

For the analysis of Packet Error Rates (PER) an approach, which was former discussed in [10] and which is based on classic Bluetooth, is adopted for the circumstances of BT5. As above introduced 79 classic BT channels are reduced to namely 40 channels, whereby 37 channels are used as data channels and 3 for advertising purposes. Furthermore, the mentioned basis is enhanced by considering the introduced interference scenarios. The derived analytical model is implemented for the above introduced assumption that all packets of a connection interval are broken in case of an error with the corresponding interval. Considering the above introduced simplifications Equation 9 depicts the implemented analytical model within this work

$$PER = 1 - \left(\frac{37 \cdot S_{BT} - 1}{37 \cdot S_{BT}} \right)^{2(n-1)\cdot G} \qquad (9)$$

with n as the number of interfering BT5 devices, S_{BT} as usable spectrum for BT5 connectivity and G as activity level of individual piconets.

B. Simulation model for Collision Probability

In order to verify the analytical model, this work implements the new hopping algorithm introduced with Bluetooth 5.0, namely Channel Selection Algorithm #2 [8] shown in Figure 6. The algorithm generates a random number for each hop using a random channel Identifier for each piconet and a counter which is initialized at connection start and incremented with every connection event. The output of the random number generator modulo 37 defines the next unmapped channel. If it is a usable channel it is the next channel in the hopping scheme, if not a remapping index is calculated with Equation 10 and the next channel in the hopping scheme is taken from the remappingTable with the remappingIndex.

$$remappingIndex = \lfloor N \cdot \frac{prn\_e}{2^{16}} \rfloor \qquad (10)$$

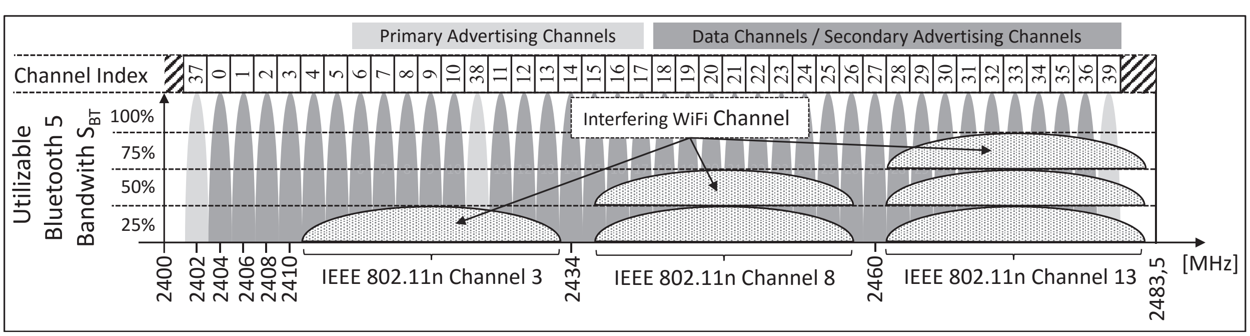

Fig. 5: Bluetooth 5 channel mapping and considered IEEE 802.11n interfering channel scenarios

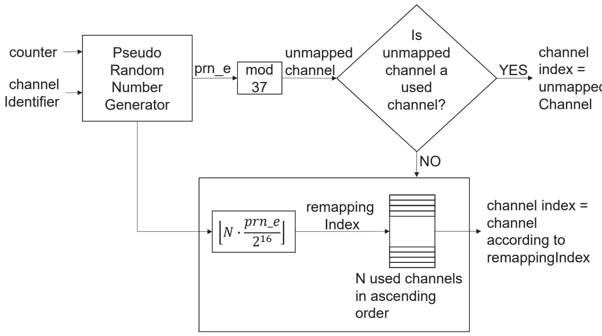

Fig. 6: Simulation Model for BT5 Channel Selection Algorithm

The above introduced and in Figure 6 illustrated channel selection approach (frequency hopping) is implemented in GNU R resulting in matrix representations for every single piconet hopping sequence, whereby piconets are considered as 1 by 1 connections. On this occasion, hops are represented by rows and piconets by columns. Based on this, hops are determined as collisions if the same channel index is detected more than once in one row of the related matrix, which refers to the same $connInterval_n$. In order to consider asynchronous BT systems, channel indexes are also analyzed for the following $connInterval_{n+1}$. Finally, packet error rate is calculated following Equation 11, also assuming that all packets of one connection interval are lost in case of a collision. Results of this AFH algorithm simulation approach are used to verify the analytical model in Section IV.

$$PER = \frac{ppI \cdot collisions}{ppI \cdot hops} \tag{11}$$

As input parameters the simulation relies on the number of piconets n, related activity level G, number of available channels S_{BT}, number of hops to be simulated and size of the connection interval.

V. Evaluation of the suitability of Bluetooth 5 for the Internet of Things

This section is constituting the evaluation of the suitability of BT5 for IoT applications covering different activity levels. First off, the representation of all considered IoT activity levels is introduced as basis for the performance evaluation.

A. Realistic Acitivity Levels for Internet of Things Applications

The performance evaluation is based on various activity scenarios that are illustrated in Table IV and rely on realistic IoT use cases. The first two activity levels of $G = 1$ and $G = 0.2$ are classic BT scenarios, such as video or audio streaming services, that are not indicated by a number of events per day, due to the reason that these use cases typically implement a continuous communication at a specific data rate. Since BT5 and the related capability of LE 2M PHY mode that provides a peak data rate of about 1.4 Mbit/s even such high data rate requirements can be fulfilled with a low energy BT variant. Due to the reason that this work is focusing on the usability of BT5 for IoT purposes, the following activity levels $G > 0.01$ are not considered during performance evaluation.

TABLE IV: Bluetooth 5 Activity Scenarios

Activity Level	**Events per day**	**Sample Use Cases**
G=0.1	*continuous*	Video Streaming
G=0.2	*continuous*	Voice and Audio Streaming
G=0.01	500 to 1000	Traffic Congestion
G=0.001	50 to 100	Noise Monitoring
G=0.0001	5 to 10	Tap Water Observation
G=0.00001	1 to 2	Smart Lighting, Waste Mgmt.

Based on this, the performance evaluation is implemented with activity levels of $G = 0.01$ down to $G = 0.00001$ substituting the overall range of IoT applications, assuming that one event is realized based on a small machine type communication protocol, such as MQTT [11]. The highest activity level of $G = 0.01$ is representing a service with 500 up to 1000 monitoring events per day (e.g. Traffic Congestion Monitoring), whereby the smallest activity level is considering IoT use cases with 1 or 2 events per day (e.g. Smart Lighting or Waste Management).

B. Performance and Scalability Evaluation

The performance evaluation relies for both, the analytical model (Section IV-A) and the AFH simulation (Section IV-B), on the parameter set listed in Table V. First off, the analytical model is verified by means of the simulation.

TABLE V: Scenario parameter for performance evaluation

Parameter	**Value range**
Activity Level G	0.01, 0.001, 0.0001, 0.00001
Aval. BT5 bandwidth S_{BT}	100%, 75%, 50%, 25%
Number of BT5 piconets n	0 to 2000
Connection Interval	7.5ms
Considered frequency hops	5000
Number of simulation runs	25
Maximum allowed PER	1%

The corresponding verification results are illustrated in Figure 7, whereby the Packet Error Rate (PER) is printed for an activity level of $G = 0.01$ and the four introduced interference scenarios. It can be shown that the match between analytical model results and simulation is very good and only differ with a mean deviation of about 0.16 %. As a result of this good match, in the following all performance results are achieved by means of the analytical model.

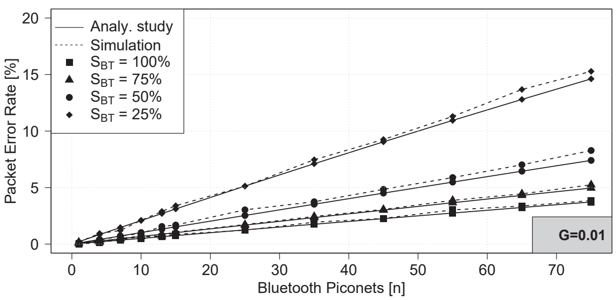

Fig. 7: Verification of analytical model by means of Adaptive Frequency Hopping (AFH) simulation

In addition to the previous verification considera-tion, Figure 8 presents the performance results for all BT5 IoT activity scenarios introduced in Table IV. For the following analysis we assume a maximum allowed error rate of $PER = 1\%$, in order to guarantee a highly reliable IoT communication link. It can be shown that the resulting PER is significantly varying related to the considered activity level as well as the interference situation within the ISM band. Starting with the highest activity level of $G = 0.01$, which represents 500 to 1000 communication events per day, the PER is increasing very fast with rising number of considered Bluetooth piconets. The maximum PER limit only results in a usable capacity of 20 piconets in case the ISM frequency band is free of any interferer ($S_{BT} = 100\%$) and reducing to even 5 piconets as usable capacity limit, when the utilizable bandwidth for the BT5 systems is reduced to 25%, due to collocated WiFi systems. Finally, in case of the smallest activity level $G = 0.00001$, a significantly higher capacity limit is determined with a limit of 19849 BT5 piconets at a PER of 1% for a non-interfered 2.4 GHz ISM band. Even at the highest considered interference level of $S_{BT} = 25\%$, it is possible to operate 4770 BT5 piconets in the same coverage area. As finding of the performance evaluation presented in Figure 8, Figure 9 summarizes the capacity limits of BT5 piconets in the same coverage area at a PER of 1%. All in all the presented performance and scalability results demonstrate that, dependent on the interference situation and especially the activity level, a huge amounts of piconets can be operated in parallel and thus BT5 is a valid technology candidate for implementation of IoT applications. Finally, in Section V-C some considerations that can be derived from above presented results are presented in term of a short case study.

C. Considerations for Network Planning purposes of Internet of Things Deployments

The above presented performance and scalability results evaluate the maximum capacity limit of BT5 piconets that can be operated in parallel. This information allows to identify the usability of BT5 for

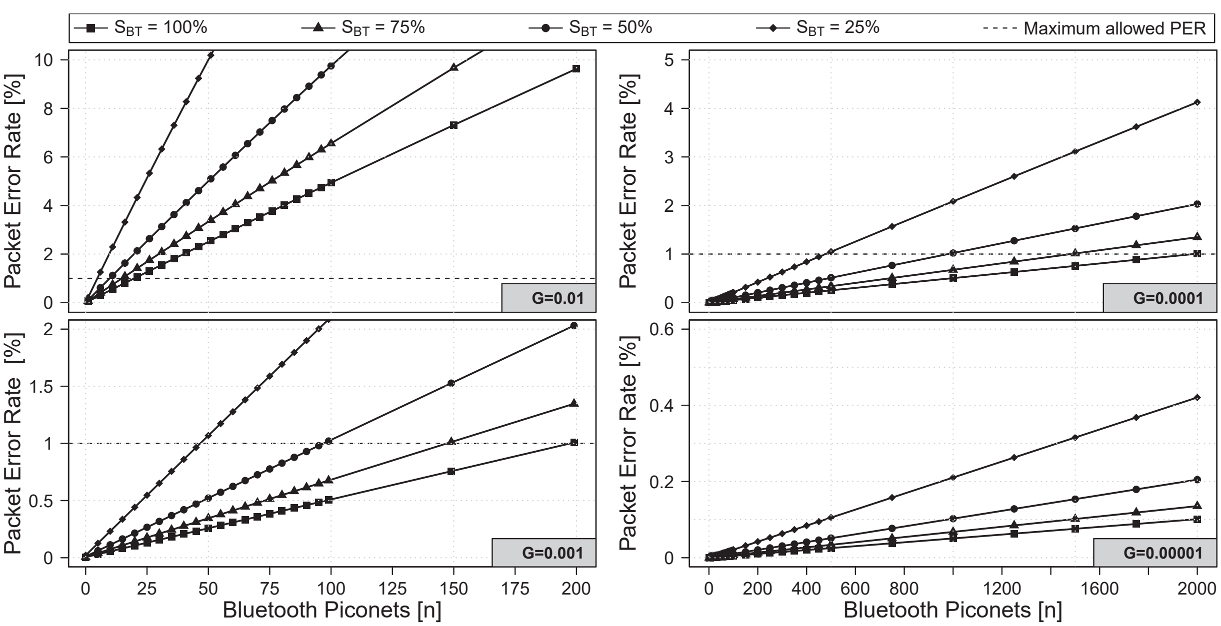

Fig. 8: Packet Error Rate (PER) for relevant IoT activity scenarios

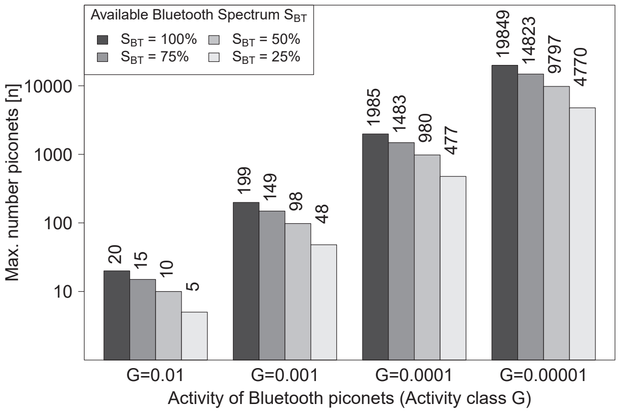

Fig. 9: Limit of Bluetooth 5 piconets for different activity scenarios at a maximum Packet Error Rate of 1%

IoT purposes, but for real world BT5 deployments we need to consider the maximum coverage area, the expected number of IoT devices and the expected activity level. The necessary information of communication range and corresponding data rate is given in Figure 4. As introduced before, in this work we focus on the LE Coded PHY (S=2, S=8) modes, due to the best IoT fit. Starting the discussion with the deployment of a Traffic Congestion Monitoring use case, which belongs to the highest activity level of $G = 0.01$. Due to the high activity level, we should consider the LE Coded PHY S=2, offering a higher data rate. The considered use case (Traffic congestion) can e.g. be deployed at a crossing, where only a small coverage area needs to be covered and a minimum transmit power can be implemented to achieve a feasible maximum communication range. Coming back to the capacity limits, the deployment also needs to consider the interference situation in the 2.4 GHz ISM band as well, because in case of the highest evaluated interference scenario only 5 piconets ($S_{BT} = 25\%$) can be operated in parallel. This might not be enough to fulfill use case requirements, while in contrast a lower interference probability allows a feasible capacity limit of 15 BT5 piconets ($S_{BT} = 75\%$), which might be a sufficient number of devices to reliable monitor the traffic density at a crossing.

VI. Conclusion

In this paper we present a performance evaluation for the suitability of BT 5 for IoT applications. The performance analysis is performed on the basis of an analytical method, which is verified by a simulation of the AFH mechanism. The performance evaluation considered realistic IoT activity levels and is performed for different extents of interference scenarios caused by WiFi systems that are collocated in the 2.4 GHz ISM band. Performance results verify that BT5 is a feasible technology solution for implementation of IoT applications, whereby the activity level, expected coverage areas and the interference situation within the ISM band needs to be considered implicitly. In future work, we aim at extending the methodical approach for performance analysis to consider path loss modeling and varying connection interval duration to cover its effects on performance and battery management, as well as BT5 mesh capabilities.

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