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***Abstract*—Bluetooth Low Energy (BLE) is a promising 2.4 GHz technology for Body Area Networks (BAN) in healthcare and lifestyle applications. However, the global increase of wireless devices using the crowded spectrum in the 2.4 GHz frequency band can create coexistence issues. This work studies the performance of BLE in environments with multiple BLE devices. An experimental setup consisting of 10 BLE nodes is used to measure BLE application throughput with different connection parameters and under different interference sources, such as other BLE devices and WiFi. The results quantify the decrease of the application throughput and the influence of BLE connection parameters in the experimental settings, as well as suggest parameter values suitable for densely deployed environments.**

***Index Terms*—Bluetooth; Low energy; Throughput; Interference; Coexistence; Body sensor networks.**

I. Introduction

Bluetooth Low Energy (BLE) is a wireless technology developed by the Bluetooth Special Interest Group (SIG) to connect devices in short range. As the name of the technology suggests, the main feature of BLE is low power consumption which in combination with an extensible framework to exchange data, has created a massive market with low-power, task-specific, creative and innovative products. Since the introduction of BLE in 2010, it has been widely adopted in mobile devices and a great variety of applications, e.g. wearable electronics, automotive applications, domestics and smart houses, gaming, security, object positioning, marketing and others [1]. BLE is considered one of the key technologies in the evolution of body area networks (BAN) [2]. The global wireless sensors market is estimated to substantially grow over the period from 2015 to 2022 [3] and the statistics portal "Statista" estimates that in 2020 the average device count per person will reach the ratio of 6.58, resulting in 50 billion devices all around the world [4].

However, the limited bandwidth of wireless sensors can hinder the market growth. BLE operates in the unlicensed 2.4 GHz Industrial, Scientific and Medical (ISM) band deployed by many other technologies like Classic Bluetooth, WiFi, Zigbee, microwave ovens and other. Multiple BLE features in Bluetooth Core specification [5] are included to improve flexibility, compatibility and efficient use of resources: space, time, spectrum and energy.

One of the largest contributors in wireless sensor market are healthcare and lifestyle applications. This study is carried out in the scope of the ERA-Net Flagship project CONVERGENCE – "Frictionless Energy Efficient Convergent Wearables for Healthcare and Lifestyle Applications" where the main concept is to develop an energy efficient wearable platform with embedded wireless low power biometric and environmental sensors.

As was mentioned before, the popularity of BLE is growing, however, owing to complex multiparameter BLE communication channel configuration possibilities and huge variety of areas of use, there is a lack of studies addressing BLE performance at application level for high throughput applications in crowded areas where many BLE devices are operating simultaneously. The main goal of this work is to experimentally check the performance of BLE protocol in densely deployed areas and crowded ISM band.

The paper is organized as follows: in Section II, related work regarding BLE throughput evaluation is presented. In Section III, theoretical application throughput limits are calculated according to BLE protocol specifications. In Section IV, experimental setup for application throughput measurements is described. In the Results and Conclusions sections, experimental application throughput measurements are presented and evaluated.

II. State of the Art

Bluetooth Low Energy (BLE) was introduced in 2010 as a part of Bluetooth core specification Bluetooth 4.0, and it was further improved in versions: 4.1, 4.2, 5.0 and 5.1 (the latest version at this time [5]).

BLE coexistence with other ISM band technologies is studied in multiple previous works. Silva *et al*. [6] conducted tests in an anechoic chamber measuring transmitted, received, re-sent and failed packets in the influence of a single interferer (classic Bluetooth, ZigBee or WiFi). Natarajan *et al*. [7] examined the coexistence between IEEE 802.15.4, BLE and IEEE 802.11. They

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performed mathematical analysis of cross-technology interference in the physical (PHY) layer and verified analytical results with experiments measuring packet-error rate. Al Kalaa *et al*. presented in [8] an analytical model for selection probability of 37 BLE data channels and used it to evaluate the probability of BLE collisions and aggregate throughput. La et al. developed a wireless testbed to conduct experimental studies, focusing on BLE and its coexistence capabilities in dense environments [9].

Marawaha *et al.* [10] performed experimental measurements using nRF52 development kits to determine BLE throughput variation for single connection by varying connection interval and application data payload size. In this work background interference was not considered.

The IETF 6LoWPAN Working Group has identified BLE as a key technology for the Internet of Things and is currently writing a specification for the transmission of IPv6 packets on top of BLE [11]. Also, as previously mentioned, the BLE gives tremendous amount of flexibility in any kind of applications. But, according to multiple papers, BLE protocol presents some constrains and bugs. Simulation results of channel selection probability has been presented to conclude that the algorithm does not provide fair usage of available data channels [8], [12]. Also, the Bluetooth protocol is vulnerable to multiple types of attacks, as shown in [13].

Previous studies have indicated, that BLE PHY layer is resilient to interference in ISM band [6], [7], [9]. However, currently there is a lack of studies evaluating BLE performance in crowded environments at application layer. BLE communication channel configuration presents multiple parameters, and a negligent selection of them could lead to the performance reduction not only due to non-optimal in-channel conditions (For example: data generation and refresh rate could be higher than current BLE channel throughput), but alto due to higher sensitivity to certain environmental conditions.

III. Theoretical Application Throughput of BLE

According to Bluetooth core specifications 1 Mbps (1M) and 2 Mbps (2M) PHY layer data rates are supported for BLE protocol uncoded data transmission [5]. However, it does not reflect BLE throughput limitations at upper layers. At the application level the throughput can be expressed as in (1)

$$S_{app} = N \cdot L_{app} / T_{ci}, \tag{1}$$

where N is the number of data transmission procedures per connection interval, L_{app}, exchanged application payload (bytes) and T_{ci} the connection interval.

BLE specification defines 4 Generic Attribute (GATT) procedures (features) to exchange application data: Reading, Writing, Notification and Indication. To maximize the application throughput without expecting any Attribute Protocol (ATT) layer acknowledgment, notifications of a characteristic value often are used to reduce protocol overhead. See Fig. 1 for an example of data transmission using notifications. In the attribute protocol layer, notifications are not acknowledged, however, acknowledgement in the link layer must be received before the next data packet. Therefore, the time required to transmit a single notification can be calculated according to (2).

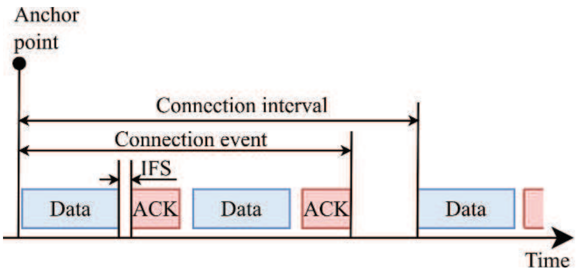

Fig. 1. Example of BLE packet communication using notifications in a connection.

$$T_{notif} = T_{data} + T_{ACK} + 2 \cdot T_{IFS}, \tag{2}$$

where T_{data} is the time required for data packet, T_{ACK}, the time required for link layer acknowledgement (empty packet) and T_{IFS}, the Inter Frame Space (150 μs).

According to uncoded BLE packet size (Fig. 2):

$$T_{data}(1M) = (17 + L_{app}) \cdot 8\mu s, \tag{3}$$

$$T_{data}(2M) = (18 + L_{app}) \cdot 4\mu s, \tag{4}$$

$$T_{ACK}(1M) = 80\mu s, \tag{5}$$

$$T_{ACK}(2M) = 44\mu s, \tag{6}$$

		PDU (0-257 bytes)							
			Payload (0-251 bytes)					
				ATT Data (0-247 bytes)				
				ATTHeader				
Preamble	Access Address	LL Header	L2CAP Header	OP Code	Attribute Handle	Application Payload	MIC (optional)	CRC
1 or 2 bytes	4 bytes	2 bytes	4 bytes	1 byte	2 bytes	0 - 244 bytes	4 bytes	3 bytes

Fig. 2. The structure of uncoded BLE packets shows BLE packet size. The size of preamble depends on PHY layer used for the connection: 1 byte for 1M and 2 bytes for 2M PHY layer.

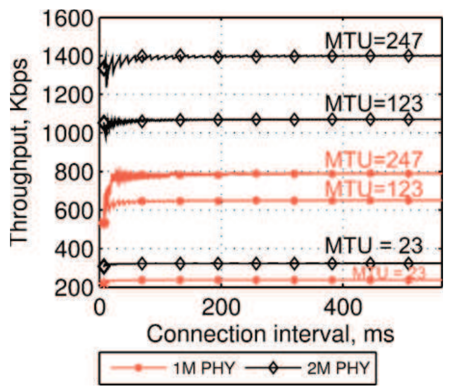

Fig. 3. Maximum BLE application throughput for 1M and 2M uncoded PHY layers. ATT MTU size values $= \{23, 123, 247\}$.

Therefore, the maximum amount of notifications in a single connection interval (N_{notif}) for corresponding PHY layer data rate can be calculated as follows:

$$N_{notif}(1M) = \left\lfloor \frac{T_{ci}}{L_{app} \cdot 8 + 516} \cdot 10^6 \right\rfloor, \tag{7}$$

$$N_{notif}(2M) = \left\lfloor \frac{T_{ci}}{L_{app} \cdot 4 + 416} \cdot 10^6 \right\rfloor, \quad (8)$$

If there are no other limitations, (3) and (4) can be used with (1) to calculate maximum application throughput depending on connection interval and notification data length (Fig. 3).

IV. Experimental Setup for Application Throughput Measurements

The schematic of the experimental setup is shown in Fig. 4. It consists of EDI Testbed network, CEA sensor platform, WiFi routers, and densely deployed BLE nodes (< 1 m range). To simultaneously control BLE devices network, the EDI Testbed [14] was used which provides remote communication and power parameter measurements for up to 100 nodes connected to the Testbed workstations. The Testbed environment was used to remotely configure BLE test devices and run test applications for throughput measurements.

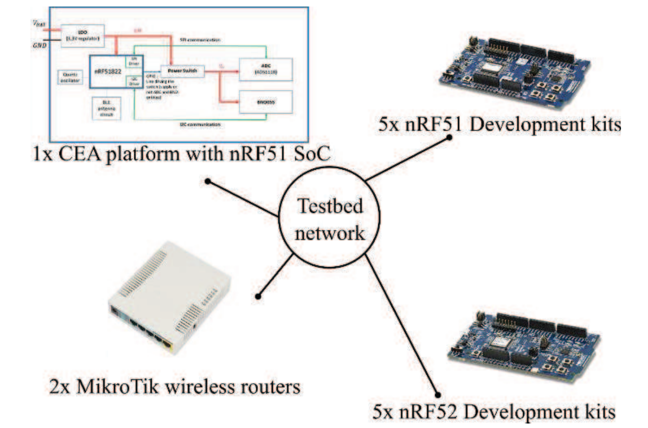

Fig. 4. The schematic of experimental setup used for BLE node remote configuration and test measurements.

The CEA sensor platform is based on nRF51822 BLE SoC and has been developed for sensor data acquisition and data transfer over BLE. The platform is compatible with different kinds of sensors to interface with the sensors provided by the CONVERGENCE project partners.

NRF51 and NRF52 development kits are low-cost, versatile single-board development kits for BLE applications. They support nRF51yyy[2] and nRF52yyy[3] SoCs accordingly [2-3]. Developments kits were used to simulate crowded BLE environment and measure average application throughput.

Experiments were conducted in a special test room to minimize ISM band interference from external sources. To ascertain the occupancy of the ISM band, a spectral analyzer was used. Initially, when all the devices were turned off, the background interference of the test room was measured. The results are shown in Fig. 5. The spectrum analyzer revealed minimal WiFi interference on the 11th channel, however, for the rest of the ISM band the interfering signals were below the noise level.

To measure the BLE throughput, the Nordic Throughput example from the Software Development Kit version 14.2.0 was adopted. The application is configured to initiate the connection between two nRF52 DK nodes and capture the average throughput transferring 1 Mbyte (10^6 bytes) of ATT payload. The application is controlled through serial command interface using dedicated serial port of the Testbed workstation.

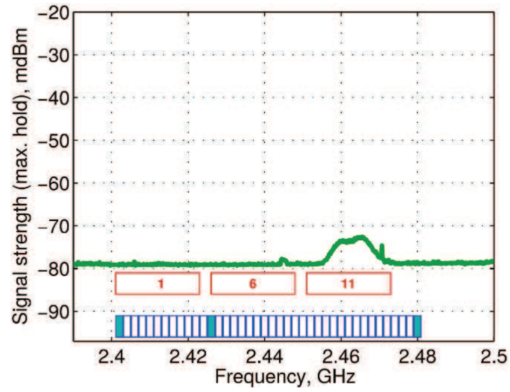

Fig. 5. The spectral occupancy of the ISM band in the test room when all the devices are turned off.

Testbed workstations and the serial command line interface enable remote reconfiguration of connection parameters (connection interval, packet size, physical layer and data length extension) and test result logging. These features are used to automate BLE tests with different configurations:

– Connection interval $\in [7.5; 400]\, ms$

– ATT MTU size $= \{23, 73, 123, 223, 247\}$

– PHY layer $= \{1M, 2M\}$

– Background BLE pairs $\in [0; 4]$

Background BLE pairs are running the Nordic *Uart app examples* from the Software Development Kit versions 14.2.0 and 10.0.0. The *Uart app example* emulates an UART interface between two Testbed serial ports using BLE protocol. The application is adopted to use static connection parameters for all connections: 7.5 ms connection interval, 23 ATT MTU size and 1M physical layer. To generate background BLE traffic, a simple Python script continuously sending 20 bytes of data to a dedicated serial port for each background device connection is used. The spectrum occupancy of the ISM band when background devices are active is shown in Fig. 6.

To evaluate WiFi impact on the BLE throughput two WiFi routers communicating on the 1st channel are used. The WiFi is configured to use 1500 Bytes of User Datagram Protocol (UDP) packets in both directions. The average data Tx/Rx speed of 6.1 Mbps/4.8 Mbps is observed which is approx. 11 % of the maximum. The spectrum occupancy of the ISM band during the WiFi traffic is shown in Fig. 7.

V. Results

Throughput measurements were taken changing the connection interval, ATT MTU size, PHY layer and the amount of background interference. Results taking the

[2] The selection of NRF51 DK is based on that the one in CEA Sensor platform. nRF51 is used and the goal was to test BLE usability for project purpose

[3] After several tests, project partners noticed that computational powers of NRF51 are too low, so the next prototype will be based on NRF52, so we decided to include NRF52 to our experiments

average of at least 3 measurements are used (see Fig. 8).

In Fig. 8, is shown how Bluetooth throughput changes, depending on background environment. Based on previously mentioned data the following conclusion could be given – the more Bluetooth devices are working simultaneously, the more drastically Bluetooth throughput is decreasing. The Bluetooth co-interference causes throughput decrease for longer connection intervals. This behavior could be explained by collisions in data transfer channel. When the hopping algorithm of two or more pairs hits the same channel, the whole time slot is lost and transmission should be repeated during next connection interval on different channel, so the longer connection interval is, the bigger are throughput losses.

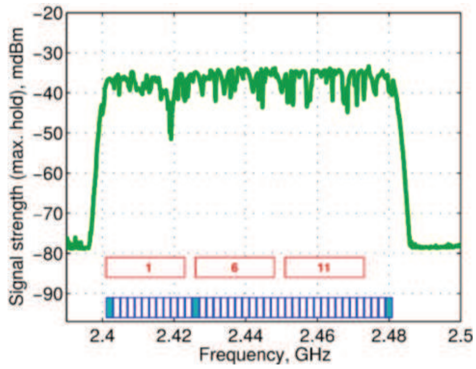

Fig. 6. The spectral occupancy of the ISM band in the test room when BLE devices are operating in connected state.

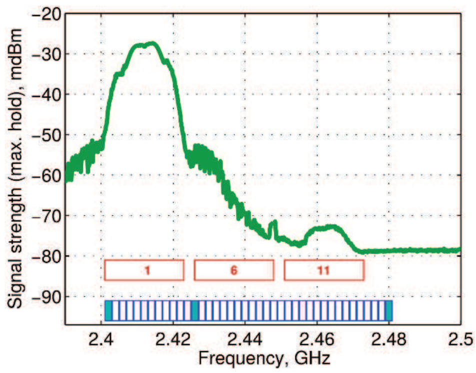

Fig. 7. The spectral occupancy of the ISM band in the test room when only the WiFi is operating.

To compare experimentally measured application throughput with theoretically expected values, the efficiency of data transmission $\eta_{protocol}$ was calculated

$$\eta_{protocol} = \frac{S_{\exp}}{S_{protocol}}, \quad (9)$$

where $S_{\exp}$ is the throughput measurement of the experimental setup and $S_{protocol}$ the maximum theoretical BLE throughput for the experimental setup configuration referring to (1). Results are shown in Fig. 9.

In Fig. 9(f) is shown WiFi influences on single pair of Bluetooth device. The interesting thing is that throughput decreases on whole connection interval range unlike with Bluetooth. The WiFi, in turn, looks like is decreasing Bluetooth throughput by constant coefficient.

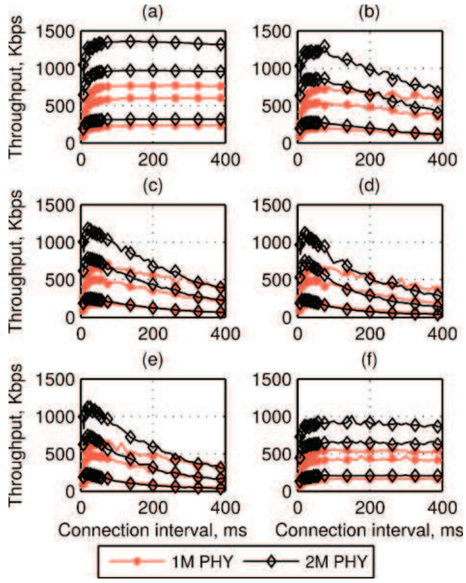

Fig. 8. The influence of BLE background devices on BLE application throughput: a) all background devices turned off; b) 1 background BLE pair operating; c) 2 background BLE pairs operating; d) 3 background BLE pairs operating; e) 4 background BLE pairs operating; f) WiFi operating on channel 1. For each PHY layer each line corresponds to different ATT MTU size = {23, 123, 247}.

To evaluate the impact of background devices, all throughput measurements were compared to initial measurements, when all background devices were turned off

$$\eta_{background} = \frac{S_{\exp}}{S_0}, \quad (6)$$

where $\eta_{background}$ is the throughput ratio with respect to empty room, and S_0 the throughput measurements when all background devices are turned off. Average $\eta_{background}$ across all measurements for selected connection intervals and PHY layers are shown in Fig. 10.

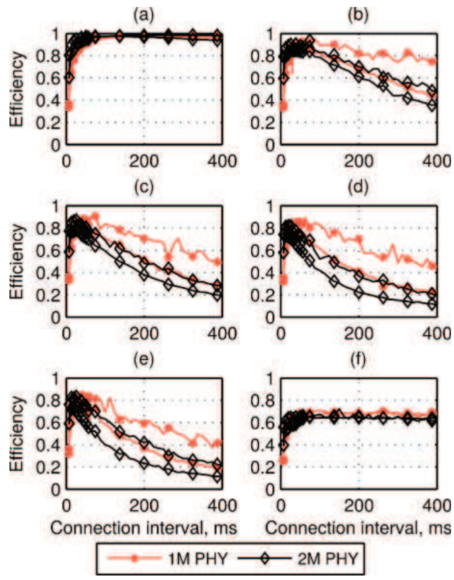

Fig. 9. BLE application throughput with respect to theoretically expected values: a) all background devices turned off; b) 1 background BLE pair operating; c) 2 background BLE pairs operating; d) 3 background BLE pairs operating; e) 4 background BLE pairs operating; f) WiFi operating on channel 1. For each PHY layer each line corresponds to different ATT MTU size = {23, 123, 247}.

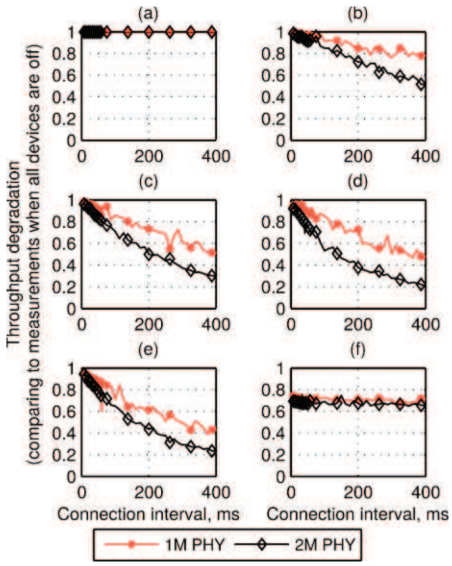

Fig. 10. Average BLE application throughput with respect to measurements when all background devices are turned off: a) all background devices turned off; b) 1 background BLE pair operating; c) 2 background BLE pairs operating; d) 3 background BLE pairs operating; e) 4 background BLE pairs operating; f) WiFi operating on channel 1.

VI. Conclusions

In this study, BLE protocol application throughput was tested with up to four concurrent background BLE connections simulating crowded environment. Even with a single background device for large connection intervals results revealed substantial deterioration of BLE protocol application throughput. According to Fig. 10, increasing the connection interval increases the susceptibility of application throughput to simultaneously operating BLE devices in densely deployed environment. However, additional tests are required to determine how it is influenced by different connection parameters used on the background devices.

Results suggest that 1M PHY layer is less susceptible to crowded BLE device environments: nevertheless, 2M PHY layer provides higher application throughput.

The effect of WiFi interference does not depend on the BLE connection interval. In this study, WiFi activity reduced BLE throughput approximately by 30% regardless of the connection interval.

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