Power Consumption Analysis for the Development of Energy Efficient Bluetooth 5 Based Real-Time Industrial IoT Systems

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Abstract. Recent improvements in embedded device hardware have led to increased performance and energy-efficiency, enabling the development of new low-power Industrial IoT (IIoT) solutions. When it comes to the development of energy efficient industrial systems, the most commonly used options are Low Power Wide Area Networks (LPWAN) technologies. However, these sub-Gigahertz technologies are often limited in terms of transmission due to duty cycle, so they are not a viable option when it comes to sending constant data flows in real time. The 2.4 GHz band is an option for these cases and, for power-constrained devices, Bluetooth is a reference technology in terms of low power consumption. Nevertheless, communications have frequently a short range, so it is usually difficult to use it in IIoT harsh scenarios. To tackle these issues, the new Bluetooth 5 standard introduces a new transmission mode (Bluetooth 5 LE Coded) that allows a longer range, thus improving the link budget and providing an increase of the sensitivity. In this paper, we analyze the power consumption, transmission times and range of a real-time IIoT system developed on Bluetooth 5, comparing its results with the Bluetooth Legacy version. For this purpose, several tests were carried out with different configuration parameters and in different transmission modes. The performed experiments allow for concluding that LE Coded offers significant advantages respect to Legacy with similar power consumption.

Keywords: Bluetooth 5 · Power consumption · Energy efficiency · Real-time · Coverage · IIoT

1 Introduction

The latest advances in the technologies involved in the IoT paradigm have progressed significantly, and more and more solutions are being offered by the manufacturers to improve diverse features. One of such features, which is common to the developers of most IoT technologies, is power consumption, since devices

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are becoming more efficient in terms of energy, which makes it possible to use alternative power supply mechanisms like energy harvesting.

Another aspect in which there is a variety of alternatives is the communications between the devices, which can be deployed conforming different topologies, such as stars, mesh networks, rings or trees. The technology of the communications link can also vary: while some technologies are designed for long range and low-frequency data transmission, others have been devised for short range and more frequent transmissions. For instance, the most popular Low-Power Wide-Area Network (LPWAN) technologies make use of star topologies and have been devised for long range communications. To achieve such long ranges, sub-1 GHz bands are used, whose use may involve certain data transmission restrictions, like the existence of duty cycles for technologies that operate in license-exempt bands (e.g., LoRaWAN) to avoid excessive channel occupancy.

A frequency band that is widely used by IoT technologies is the 2.4 GHz Industrial, Scientific and Medical (ISM) band. There is a significant number of technologies that use this band for IoT applications, including ZigBee, Bluetooth, WiFi (i.e., IEEE 802.11 b/g/n/ac) or Thread. The devices that make use of such technologies tend to operate in the opposite way to the ones that make use of LPWAN technologies, as there are no duty-cycle restrictions for sending data, but they can use low transmit power levels if they are operating on constrained power sources.

Bluetooth is an example of a widely used communications technology for low-power short-range devices like wearables or real-time monitoring sensors [1]. The latest version of Bluetooth (Bluetooth 5) has improved numerous aspects of the protocol, providing more bandwidth and better response times, as well as increased range and less power consumption [2]. This paper presents a development based on such a new Bluetooth standard, which was used by the authors through the Joint Research Unit between UDC and Navantia [3] for creating a sensor to monitor oxygen concentration levels. The main objective of the developed system is to provide oxygen level measurements and display alarms in confined spaces, where oxygen concentration levels may vary due to certain tasks performed by industrial operators (e.g., argon welding). Specifically, such oxygen concentration levels can be displayed in real time and alarms are triggered when the oxygen level drops below a certain level or when the Bluetooth connection is lost.

The system presented in this paper is intended for being used in industrial environments, where, due to electromagnetic interference and shielding from metal objects, it is particularly challenging to achieve stable real-time communications. This can be accomplished thanks to the use of the Bluetooth LE Coded mode, which reduces the data rate to 125 Kb/s and adds more data to the frame to make use of error correction, which enables to decode the frame up to 4 times farther without increasing the transmission power. This provides extra sensitivity and improves the link budget, which is important in industrial environments. However, it should be noted that, although the use of LE Coded does not imply an increase in transmission power, sending longer frames involves longer transmission times (up to 8 times longer), which increases energy consumption and is not valid for all situations (as it will be discussed later in Sect. 4).

The rest of this article is structured as follows. After reviewing the background knowledge in Sect. 2 and describing the developed system in Sects. 3, 4 and 5 analyze the key aspects that impact the energy consumption of Bluetooth 5 in the developed system. Finally, Sect. 6 is devoted to the conclusions.

2 Background

2.1 Wireless Low-Power Communications: Bluetooth Versus ZigBee

The IIoT system proposed in this paper was designed to make use of the 2.4 GHz band to take advantage of time-unrestricted transmissions. In such a band, there are several wireless technologies that provide low power features, being ZigBee, which is based on the IEEE 802.15.4 standard, one of the most popular.

Bluetooth is another low-power technology that has evolved remarkably in the last years. In fact, there are already in the market Bluetooth 5 commercial System-on-Chips (SoCs), like nrf52840 and nrf52833 from Nordic Semiconductor, which are able to act as Bluetooth, ANT, ZigBee 3.0 or Thread 1.1 transceivers. This kind of modules enables the creation of hybrid systems, which can make use of, for example, ZigBee and Bluetooth. However, it must be considered that two radio modules that operate in the same frequency band with different protocols can cause interference and channel saturation problems, especially when there are continuous transmissions, as it was previously analyzed in [4] and [5] (such paper show how interference affects ZigBee when it is used simultaneously with another wireless protocol).

With respect to ZigBee modules, the DigiXbee EFR32MG SoC is widely used. The datasheet provided by the manufacturer specifies an indoor range of 60 m and outdoor range of 1,2 km with a power of 8 dBm [6]. There is also an XBee 3 Pro version that triples the previously mentioned range values of the Digi XBee 3 board, but it makes use of 19 dBm of transmit power, which cannot be supplied in a continuous way by most battery-powered devices.

Dementyev et al. [7] carried out a study that compared Bluetooth Low Energy (BLE) and Zigbee, concluding that BLE was able to achieve a lower consumption than ZigBee. In fact, the results show that, theoretically, BLE has a better ratio between data transfer and consumption, while IEEE 802.15.4 has more coverage range due to better sensitivity. However, the new LE Coded PHY of Bluetooth 5 adds more sensitivity while reducing the bitrate.

Due to the previously mentioned studies, it can be stated that ZigBee does not provide any improvement in sensitivity and range with respect to Bluetooth LE Coded so, the system presented in this paper is based exclusively on Bluetooth.

2.2 Bluetooth Performance

Since Bluetooth have a centimeter wavelength, it is interesting to see how its LE Coded (Long Range) mode works indoors, where there are no Line of Sight

(LoS) communications, as different materials and obstacles will affect the propagation of the signal. For example, Zhan et al. [8] measured the throughput at different indoor distances with all the different Bluetooth 5 PHYs as well as the reception sensitivity. The authors concluded that with the LE Coded PHY (S = 8, 125 Kb/s), it can be obtained the same range and a transmission power of 8 dBm less than the one needed for the Legacy version. Nonetheless, it should be noted that throughput is not a determining factor for most IIoT systems, being more important the reception signal quality.

Another important aspect to analyze is Bluetooth power consumption, since one of the goals of most IIoT developments is to minimize the consumed energy to extend the life of battery-powered devices. In the literature there is a lack of papers on the analysis of Bluetooth 5 energy consumption. One of the exceptions is [9], where the authors analyzed the energy consumption for different connection parameters for Bluetooth 5. In such a paper, the authors showed that, although Bluetooth 5 requires more power than BLE, transmission time is shorter, therefore the overall power consumption of Bluetooth 5 for sending data is lower than for BLE.

In contrast to such a publication, this paper is focused on the LE Coded mode, comparing its impact with the Legacy version and analyzing consumption, transmission times and range. In general, LE Coded mode is used to send periodical data over long distances with the highest power level (similarly to LPWAN technologies). In such a mode, Nordic Semiconductor achieved a range of 1.3 km with Line-of-Sight (LoS) when using two development kits (nRF52840-DK [10]) with a transmission power of 0 dBm [11].

In the case of confined spaces monitoring, a transmission power of 0 dBm, even though it cannot be considered as a high transmit power, it ends up consuming quite a lot of energy if frequent transmissions are performed, so it becomes a problem when operating with a constrained power source. In addition, it is worth considering that the use of the 2.4 GHz ISM band derives into using a centimeter wave that does not have a large penetration factor and, in a closed environment like a confined space, it can become completely blocked in certain areas made of certain materials (e.g., metallic surfaces) and when there is significant electromagnetic noise in the environment. In such circumstances is where the use of the LE Coded mode becomes important.

Finally, the fact that there are actually billions of interconnected IoT devices is a challenge for communications, there are currently numerous mechanisms to manage this growing number of devices connected to the Internet, IPv6 is the main alternative, although its implementation is not being as fast as expected, there are transition mechanisms that allow coexistence. In this aspect 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks) offers a very attractive alternative to manage this problem, since it allows Bluetooth devices to connect automatically to the Internet. For instance, R. Amornpornwiwat et al. [12] present a comparison of 6LoWPAN with BLE versus WiFi and Ethernet over IP, being the first one the most energy efficient.

3 Developed System

The developed IIoT system is based on a node that carries a 650 mA LiPo battery, an Arduino Nano 33 BLE (which is based on the nrf52840 SoC) [13], a KE-25 fast-response oxygen sensor [14] and a DHT-22 temperature and humidity sensor. The IIoT node sensor data are collected by mobile devices (e.g., smartphones, tablets) carried by the industrial operators which have to support Bluetooth 5 (for the experiments documented in this paper, a OnePlus 8T smartphone was used). For such a mobile device, an Android application was developed. Figures 1 and 2 show, respectively, the electronic schematic of the IIoT node and the main screen of the developed Android app.

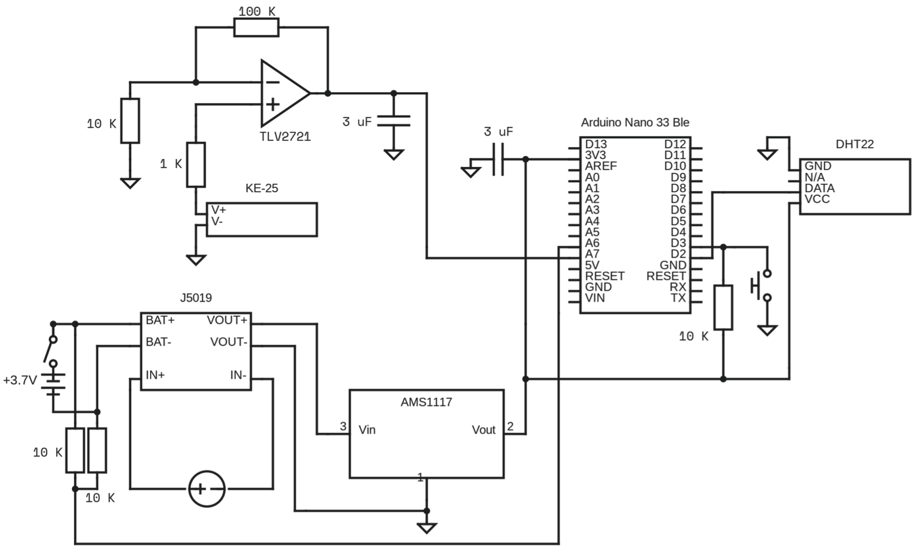


Fig. 1. IIoT node circuit schematic.

For testing and prototyping purposes, Nordic Development Kits were used (in particular, nrf52840-DK [15] and nrf52833-DK [16]). Energy consumption measurements were performed via an oscilloscope (Hanmatek DOS1102) with 110 MHz of bandwidth, 1 GS/s, ±100 ppm of sample rate and a sensitivity of 5 mV/div. Measurements were collected by using a Shunt resistor of 10 Ω. It is important to note that the hardware used for the energy consumption measurements is practical, but it does not provide the best accuracy for measuring low currents in idle or sleep states due to the scale difference. For such a reason, this paper focuses only on the events that consume the most, which are to processing and to the use of the radio module. As a consequence, energy consumption is not measured when the module is in idle or sleep, since it is too low to be quantified accurately with the selected measurement setup.

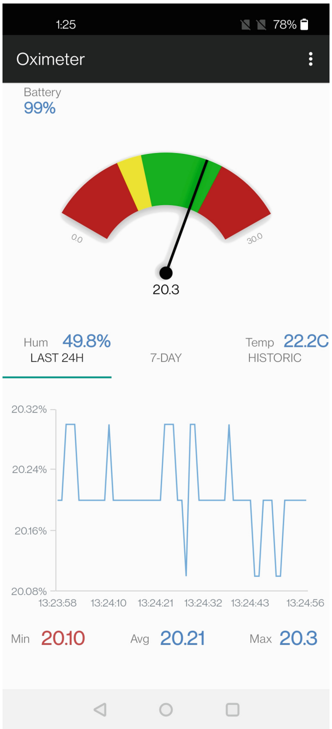
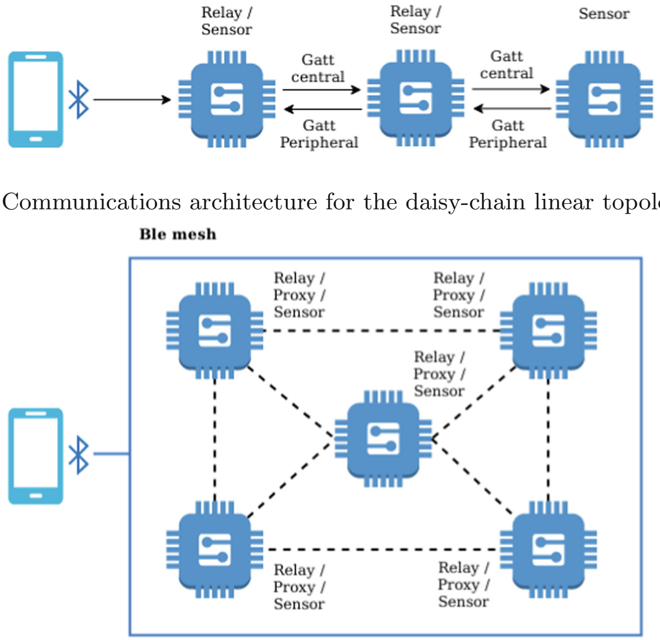


Fig. 2. Main screen of the developed Android application.

Since the developed system needs to be scalable, the energy consumption was tested with different topologies:

- A daisy-chain linear topology, where the nodes can act as sensors and relays, with two Bluetooth interfaces per node (one works as a peripheral GATT and the other one as a central GATT, using the first node as an entry-point for the Bluetooth device.
- Mesh topology. Such a type of topology is more robust, since any node can act as entry point and, being totally decentralized, nodes are able to scan for other nodes in range to retransmit data.

Figures 3(a) and 3(b) show the structure of the two topologies used in the tests.



(a) Communications architecture for the daisy-chain linear topology.

(b) Communications architecture of the mesh topology.

Fig. 3. Communications architecture for the daisy-chain linear topology.

4 Experiments and Results

Several tests were performed in order to compare energy consumption and signal coverage when transmitting in different transmission modes. Thus, the objective is to determine the optimal mode for the proposed use case that gives the best balance between consumption, coverage and deployment needs.

4.1 Energy Consumption Tests

The developed prototype described in Sect. 3 was analyzed in terms of consumption. Specifically, consumption tests were performed only for the nrf52833 module. The module internal circuitry allows to measure only the consumption of the SoC, thus isolating the rest of the components. Such an approach provides more fairness when judging the results, since it will only depend on the SoC hardware and on the firmware implemented for each test.

The passive components of the hardware prototype (i.e., power boost, voltage regulator, operational amplifier and voltage divider) consume an average of 10.4 mA.

With respect to the two used sensors, the KE-25 does not consume current: it is based on a galvanic cell that generates an output voltage depending on the oxygen levels. In the case of DHT-22, it performs measurements every 20 s and it has a consumption of 0.3 mA when measuring and 60 μA in standby. Note that, in the tested use cases, temperature and humidity do not fluctuate, so it is usually only necessary to make use of an internal thermistor to correct the calculation of the oxygen levels depending on the ambient temperature.

For the performed tests, a specific firmware was developed for each scenario. For the daisy-chain linear topology, energy consumption was measured for the two operating modes on a Generic Attribute Profile (GATT) connection: data transmission (when there is an established connection) and advertisement mode (when no connections are performed).

The parameters used in the GATT are the following:

- Advertisement time: 120 ms.
- Minimum acceptable connection interval: 20 ms.
- Maximum acceptable connection interval: 75 ms.
- Transfer time: 500 ms.

For the mesh topology, the proxy events (GATT Bearer advertisement and GATT Bearer transmission) and the mesh events (data publish event) were analyzed when using the next parameters:

- GATT Bearer advertisement time: 200 ms.
- Publish time: 500 ms.

Figure 4 shows the power consumption of the main GATT peripheral operation over time. Such a Figure shows a period of 240 ms that allows for observing how energy consumption varies over time: the first area includes two peaks that are related to advertisement events when no devices are connected (during 'LE Coded Advertising'), then a second area ('establish connection') is associated with connection establishment and includes a sequence of 9 peaks. It is important to note that the length of this area depends on the client Received Signal Strength Indicator (RSSI). The third area represents the data sending process, once the device is connected: it includes a peak due to a GATT request, while the next peak is associated with a GATT reply. Finally, the last peak is related to an additional GATT request.

To reduce power consumption, it was first decreased the transmission power. It is worth mentioning that Nordic Semiconductor provides an online tool that allows for estimating power consumption based on various Bluetooth parameters [17]. In particular, the used Bluetooth hardware allows for transmitting at −40 dBm, −30 dBm, −20 dBm, −16 dBm, −12 dBm, −8 dBm, −4 dBm and 0 dBm. Figures 5 and 6 show how energy consumption differs for the advertisement and data sending events when transmitting at −40 dBm, −20 dbm, −8 dBm and 0 dBm, respectively.

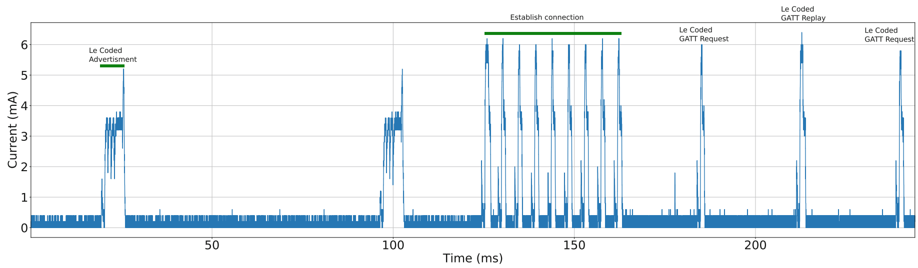


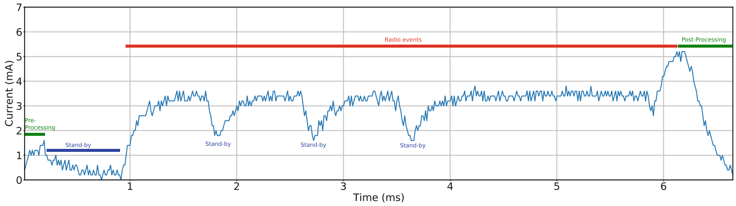
Fig. 4. Energy consumption of the main functionality of the GATT peripheral.

As it can be observed, energy savings for the analyzed Bluetooth events are not especially significant when lowering the transmission power: they go from an average of 4.77 mA in advertising and 3.09 mA in data transmission at 0 dBm, to 2.74 mA and 2.42 mA, respectively, at −40 dBm. The average consumption for each transmit power can be seen in Table 1. Although the consumption is not reduced significantly, the Bluetooth communications range drops dramatically when lowering the power levels, as it will be discussed later on in Sect. 4.3.

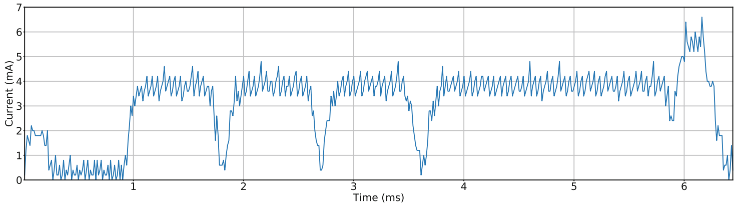
Table 1. Average consumption at different power levels for LE Coded mode.

Bluetooth event	−40 dBm	−30 dBm	−20 dBm	−16 dBm	−8 dBm	−4 dBm	0 dBm
Average Advertisement Current (mA)	2.74	2.86	3.12	3.37	3.56	4.06	4.77
Advertisement Energy Consumption (µA h)	138.9	144.9	157.9	170.4	179.9	204.9	240.4
Average Data Transmission Current (mA)	2.42	2.50	2.61	2.69	2.77	2.91	3.09
Data Transmission Energy Consumption (µA h)	5.2	5.3	5.4	5.5	5.6	5.8	6.1

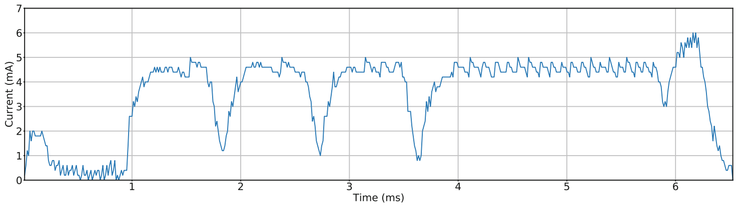
Thus, reducing transmit power lowers power consumption, existing the largest difference when broadcasting advertisements. This is due to the fact that the duration of the advertisements is longer than data payload transmissions, so the average consumption of the peaks for the advertisements is more impacted by changes in transmit power than in the case of data transmission events.



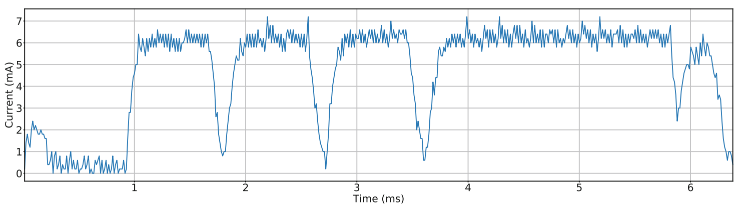
(a) Current consumed during advertising event when transmitting at -40 dBm.



(b) Current consumed during advertising event when transmitting at -20 dBm.



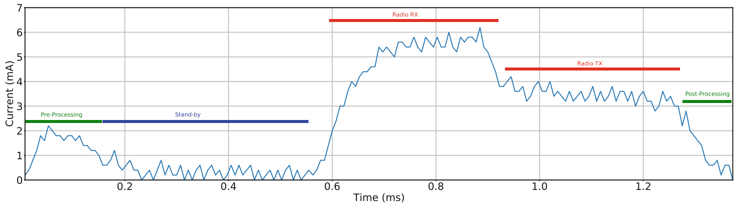
(c) Current consumed during advertising event when transmitting at -8 dBm.



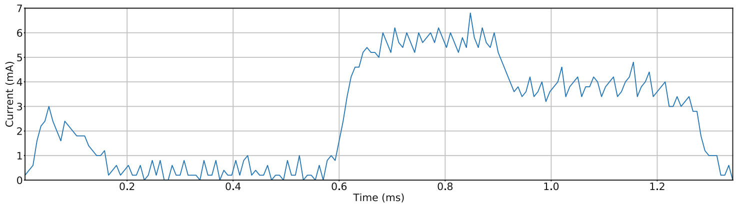
(d) Current consumed during advertising event when transmitting at 0 dBm.

Fig. 5. Power consumption for advertisements transmitted at different power levels.

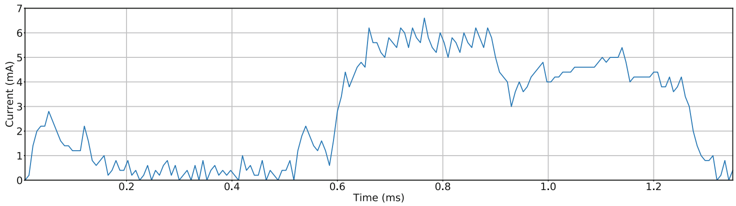
Another important point to consider is the consumption when using LE Coded mode. This mode allows for improving the communications range up to 4 times the values achieved in Bluetooth Legacy mode (physical layer used on the Bluetooth 4.x standard) when transmitting at the same transmission power. However, LE Coded mode requires more time on air for the transmissions, which implies that is necessary to turn on the radio module more time, deriving into a



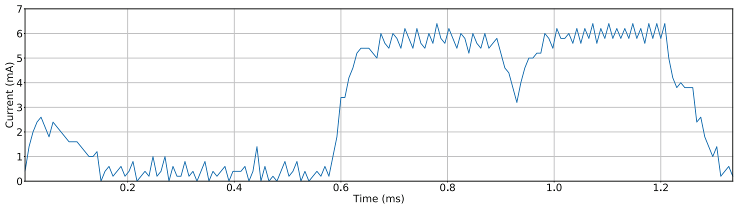
(a) Current consumed during data sending when transmitting at -40 dBm.



(b) Current consumed during data sending when transmitting at -20 dBm.



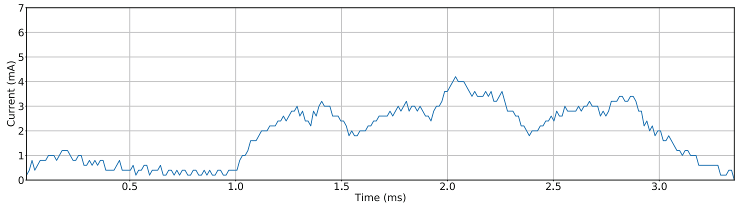
(c) Current consumed during data sending when transmitting at -8 dBm.



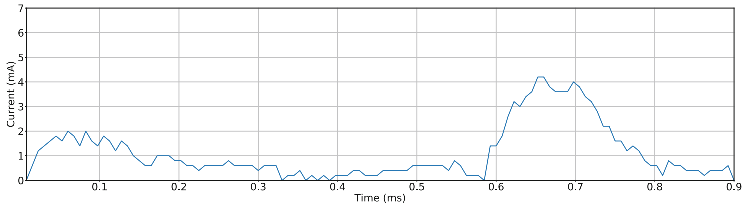
(d) Current consumed during data sending when transmitting at 0 dBm.

Fig. 6. Power consumption comparison when sending data at different power levels.

higher energy consumption. Figure 7 shows the energy consumption of an advertisement and data transmission event when transmitting at -40 dBm in Legacy mode. Such a figure can be compared with the results shown in Figs. 5a and 6a. It can be concluded that the peak values are quite similar but the amplitude of the events is significantly higher in LE Coded, especially in advertising events.



(a) Power consumption of a Legacy advertisement when transmitting at -40 dBm.



(b) Power consumption of Legacy data sending when transmitting at -40 dBm.

Fig. 7. Legacy events at the same transmission power level.

Table 2 compares the average current and event duration values for Legacy and LE Coded modes when transmitting −40 dBm. As it can be observed in the table, both data transmission and advertisement events in Legacy mode are more energy efficient than in LE Coded mode: they consume on average 1.31 mA less in the case of data transmissions and 0.89 mA less during advertisements. Moreover, the results indicate that advertisements can definitely drain more power, especially in LE Coded mode, since their duration is 3.03 ms longer than in Legacy mode. Nonetheless, it must be noted that, when using GATT peripheral, advertisements are only used when no devices are connected, so an overall lower advertisement time allows for saving energy at the expense of making device reconnections slower. In the case of data transmission events, they last only 0.43 ms more in LE Coded.

Table 2. Power consumption and duration of Bluetooth events in Legacy and LE Coded modes when transmitting at −40 dBm.

Bluetooth event	Avg. current (mA)	Duration (ms)
Data Tx (Legacy mode)	1.11	0.9
Advertisement (Legacy mode)	1.85	3.35
Data Tx (LE Coded mode)	2.42	1.33
Advertisement (LE Coded mode)	2.74	6.38

4.2 Mesh Mode

The GATT client-server mode evaluated in the previous subsection has an important limitation in operation: in a multi-node scenario it is only possible to connect to a single GATT peripheral at the same time. Therefore, when using GATT client-server mode, in order to collect information from a specific node, it is necessary to be physically in the range of such a node, requiring to disconnect from any other node.

In the mentioned multi-node scenario, a more efficient communications alternative consists in conforming a BLE mesh. The mesh is able to create a distributed network where nodes can relay information from others in range and any of them can serve as an entry point to access the network data, thus overcoming the limitation in range derived from the use of centimeter bands. However, the use of a Bluetooth mesh involves three important considerations:

- BLE Mesh is a broadcast-based network protocol, where every device in the network sends and receives all messages to and from all devices within the radio range, which implies that the radio transceiver is running constantly. As a consequence, the power consumption of a regular mesh node should be almost the same as the RX current of the radio. The reason is that the radio has to scan the radio channel continuously for packets, which involves to draw a significant amount of current. However, there is a mesh mode for low consumption: a mesh with Low Power Nodes (LPN) that allows IoT nodes to send data periodically and sleep the rest of time, thus decreasing energy consumption considerably. For instance, Mahdi et al. [18] analyzed the power consumption of an LPN node within a Bluetooth 4.x mesh: with a 235 mA battery and publishing messages every 10 s they achieved a lifetime up to 15.6 months.
- Regarding the previous point, an LPN node is not able to participate actively in the mesh on its own. Such a kind of nodes are used in certain scenarios where battery-operated devices that send periodic data need to be deployed. In such cases, the node may not be able to scan continuously, but still would want to participate in the mesh network to control and communicate with other mesh nodes [19]. The LPN makes use of a special node (Friend node) to participate in the mesh network with significantly shorter scanning duty cycle. Friend nodes can communicate and relay data through other nodes, by re-broadcasting received mesh messages. Since such an operation would require a significant amount of power, nodes need to be typically wall-powered or working with another type of continuous energy source.
- The BLE mesh mode is actually a Bluetooth 4.x standard, so using LE Coded is not supported officially. It is possible to implement a mesh that communicates using LE Coded mode, but it is necessary to consider the longer processing time and preambles of this mode by adjusting times and buffer sizes in the timeslot Application Programming Interface (API) to compensate for the longer on-air packets.

In order to evaluate the consumption performance in mesh mode, an LPN node was tested. Figure 8a shows the power consumption for a data publishing event on an LPN node with −40 dBm of power transmission. Although the showed functionality falls more on the Friend node, it is also possible for an LPN node to function as a proxy, allowing it to be used as an entry point. This functionality is not particularly costly from a usage point of view, since it only has to send advertisements when there is no device connected to the node and use GATT transmissions when it is connected.

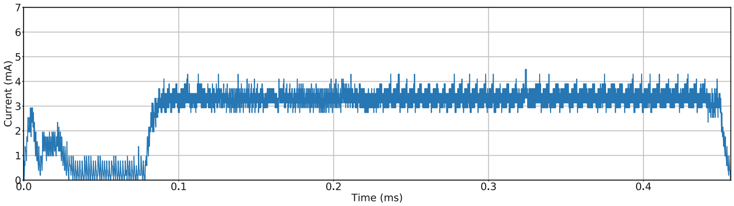
Figures 8b and 8c illustrate the energy consumption of the advertisement and GATT transmission events of a proxy LPN node, respectively. It is necessary to take into account that these events are in Legacy mode, as opposed to the LE Coded used in the publication event (Fig. 8a). This is due to the fact that Mesh mode has different layers used by the Bearer (the communications system that is used to transport data). Bluetooth mesh may be used over either of these two bearers: the Advertising Bearer or the GATT Bearer [20].

The Advertising Bearer is used to receive messages and broadcast messages from/to other nodes, while the GATT Bearer allows a device to communicate indirectly with nodes of a mesh network using a protocol known as the Proxy Protocol (which also implies that the mesh node implements the proxy role).

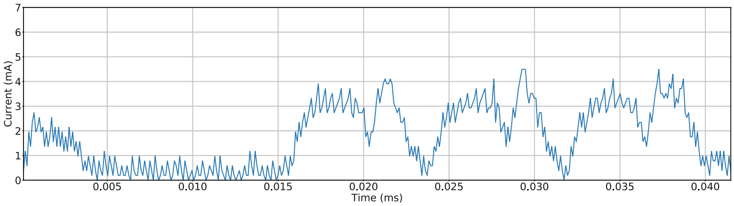
As it was previously mentioned, the mesh mode is a Bluetooth 4.x standard, so, by default, there is no implementation of the LE Coded physical layer. Nevertheless, part of the standard was implemented to make use of the PHY LE Coded. The internal communications of the mesh nodes (GATT Advertisement) was successfully implemented and properly working with this mode. The proxy protocol, in charge of using the nodes as entry point for Bluetooth devices (GATT Bearer), remained in Legacy mode.

It is possible to see the remarkable difference in the event duration between GATT client-server and mesh mode through Figs. 7, 8b and 8c. Both the advertising and the transmission event are much shorter in mesh mode than in GATT client-server mode, due to the fact that the information sent in the events is much smaller.

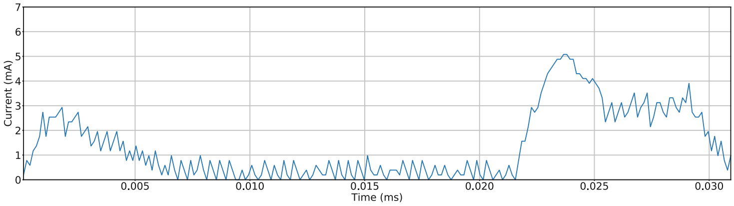
To further reduce consumption, there are two parameters directly involved, Poll Timeout and Receive Window that can be adjusted. These parameters affect directly the communications between the LPN and the associated Friend node. The LPN wakes up periodically and polls the Friend node for any new messages. The Friend node then delivers associated mesh messages to the LPN. Longer Poll Timeouts mean more time in sleep by the LPN. For longer Poll Timeouts, Receive Window becomes irrelevant [18]. However, for this particular case, since data transfer is fast (set to 500 ms), it is also possible to decrease the Receive Window, which means the radio interface needs to remain less time in receive mode.



(a) Power consumption for data publishing event on a LPN.



(b) Power consumption for GATT Bearer Advertising event on a LPN.



(c) Power consumption for GATT Bearer data transmission event on a LPN.

Fig. 8. Power consumption on a LPN.

4.3 LE Coded Vs Legacy Mode Range

This subsection analyzes the reception quality at different points when making use either of Legacy or LE Coded mode. Figure 9 shows a map of the indoor scenario in which the tests were carried out. Such Figure represents the location of the deployed nodes, as well as their antenna orientation. In this case, two independent tests were carried out: one between spots A and B with the transmission powers indicated in Table 3, and another one between locations C and D with the transmission power showed in Table 4. The mentioned tables show the RSSI values and error rates in reception obtained for each scenario.

The experimental results shown in Tables 3 and 4 indicate that reception is more stable when using LE Coded due to its higher RSSI values (up to −96 dBm in Legacy and -103 dBm in LE Coded, according to the manufacturer datasheet). In addition, the fact that LE Coded mode allows for decoding with a lower RSSI than in Legacy mode, provides an extra sensitivity for packet decoding, which is particularly interesting at points where there is low connection quality.

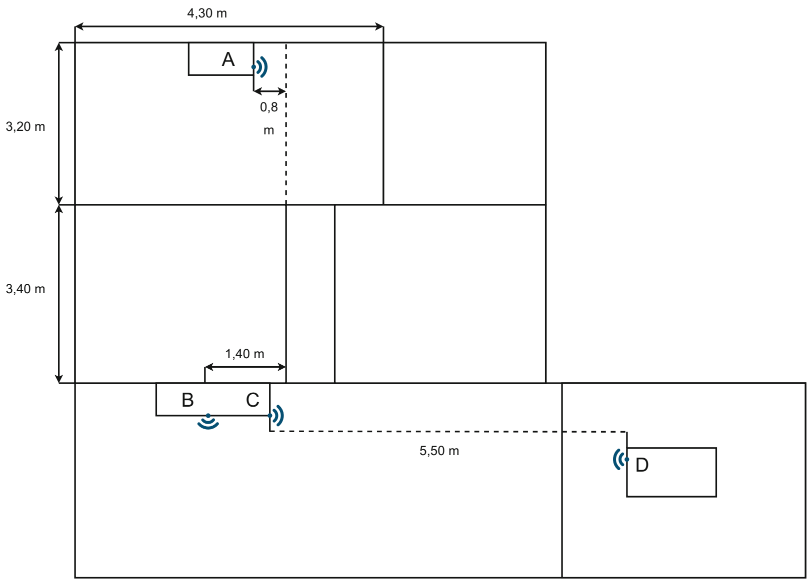


Fig. 9. Nodes layout in the indoor test environment.

At points C and D (Table 4), it can be observed that when transmitting at −40 and −30 dBm, there is a significant impact on the transmission range, losing between 70% and 67% of the packets, respectively, with LE Coded, and every packet in Legacy mode. In contrast, with a power level of −20 dBm there was no loss in both modes. In case of points A and B (Table 3), transmission power values were higher, and a more linear error rate can be observed, but a clear improvement in signal strength is obtained when using LE Coded mode instead of Legacy mode.

Table 3. Coverage results at points A and B

Power level (dBm)	Mode	Error rate (%)	Min. RSSI (dBm)	Max. RSII (dBm)	Avg. RSSI (dBm)
−16	LE Coded	17	−91	−87	−88.4
	Legacy	99	−87	−87	−87
−12	LE Coded	0	−91	−81	−84.7
	Legacy	57	−86	−81	−82.7
−8	LE Coded	0	−90	−79	−83.4
	Legacy	15	−86	−80	−82.4

Table 4. Coverage results at points C and D

Power level (dBm)	Mode	Error rate (%)	Min. RSSI (dBm)	Max. RSSI (dBm)	Avg. RSSI (dBm)
−40	LE Coded	70	−92	−89	−88.9
	Legacy	100	N/A	N/A	N/A
−30	LE Coded	67	−91	−88	−88.4
	Legacy	100	N/A	N/A	N/A
−20	LE Coded	0	−88	−78	−85.4
	Legacy	0	−87	−78	−86.1

5 Key Findings

From all the tests carried out, the following conclusions were obtained:

- There are no considerable savings in power consumption by lowering the transmitter power to the lowest levels. For instance, from −8 dBm to −20 dBm there is difference of only 0.44 mA and 0.16 mA for advertising and transmission events, respectively. The main difference is in airtime, specially in advertisements since make more use of the radio module than transmission events. In LE Coded this is much more noticeable, for instance the data transmission event last 0.43 ms more in LE Coded while the advertisement event takes 3.03 ms more.
- The GATT client/server mode is more energy efficient than the mesh mode. Nevertheless, it is a fairly simple communications mechanism and has limitations in multi-node networks. The mesh mode provides full redundant communications, but this also implies higher energy consumption. In the evaluated use case, where the frequency of data update is too high, even when using LPN nodes. Thus, the time LPN nodes remain in sleep mode is reduced and they present a considerable consumption. Taking into consideration less frequent update times, a better balance between consumption and network redundancy could be obtained.
- At the light of the obtained results, probably the best solution for the deployment of this particular case is an hybrid approach. The multi-link mode allows several GATT peripherals to connect to one central device. Then, the integration of several central devices will provide more redundancy to connectivity.
- With respect to coverage, the use of LE Coded allows for making more stable communications or even deploy less nodes. The advertisement mode in LE Coded mode consumes significantly more than legacy, since it needs to use the radio module more. It also has more time on the air and, since Bluetooth only has 3 channels for advertisement, there is a risk of saturating the band. In connection mode there is less difference between LE Coded and legacy modes.

– The LE Coded mode can definitely help low-power BLE solutions to improve the range for legacy devices that typically provide a short range of a few meters when operating at their lowest transmission levels. Although it is not widely used in these cases due to the longer duration of the frames and consequently higher consumption, the obtained times do not present significant differences among the different connection modes, especially when a payload has a reduced size and it can offer an improvement in the link budget in noise environments. With power levels of −16 dBm and −12 dBm, LE Coded outperformed Legacy mode reception rate by 82% and 57%, respectively. In addition, when transmitting at −40 dBm, the energy consumption remained stable with a slight increase in LE Coded mode (1.32 mA more) and with an event duration of just 0.43 ms longer than in Legacy mode.

6 Conclusions

The aim of this work was to perform a power consumption analysis of Bluetooth 5 LE Coded PHY and Legacy modes to develop next-generation energy efficient Bluetooth 5 real-time IIoT applications. After analyzing all the tests carried out, it can be concluded that no significant savings were obtained by lowering transmit power. In addition, the main difference between LE Coded and Legacy was in transmission time, especially for advertisement events. With respect to the different topologies evaluated, GATT client/server mode is more energy efficient that the mesh mode even when using LPN nodes. The obtained results also emphasize the importance of hybrid approaches for deployment, especially when mixing both topologies. When it comes to coverage, the use of LE Coded allows for making more stable communications. Despite its longer frame duration, which implies higher energy consumption, the obtained times do not present significant differences among the different connection modes, especially when a payload has a small size. To sum up, LE Coded can offer significant advantages in the link budget in harsh industrial environments.

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