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Bluetooth 5, Refined for the IoT

Bluetooth® 5, Refined for the IoT

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This whitepaper introduces the new features of Bluetooth 5 technology and how they enable the next wave of IoT applications. The hallmark features of Bluetooth 5 include twice the speed, four times range, and eight times the advertising capacity for long range, more robust connections, better user experience, and smarter beacons.

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Refined for the IoT

The rapidly evolving and expanding IoT market provides big opportunities for device manufacturers. New applications and the huge increase of devices requiring wireless connections has also kept various wireless standard interest groups busy developing new standards or updating existing ones to fulfill IoT-specific needs.

The projected market growth for IoT-related applications and devices varies but one estimate puts the figure at around 16% CAGR up to the year 2025 [1]. This wide range of IoT applications will require the use of not one but several wireless standards if all usage scenarios are to be realized. This in turn also implies that coexistence issues need to be addressed adequately. The increased demand for suitable gateway devices is obvious.

According to market share estimates, Bluetooth will be used in 60 percent of all wireless devices by the year 2021 and Bluetooth low energy correspondingly in 16 percent of devices. Most of the increase will be seen in smart home, beacon, connected home, and wearables applications [2]. According to the computer magazine Datamation, ABI Research is expecting Bluetooth with low energy shipments to have a CAGR of 34 percent between 2016 and 2021 [3]. Such growth requires the wireless standards to be extremely robust and dependable. What is also needed are manufacturers who utilize the possibilities allowed by the wireless standards to the maximum in their hardware offering and who provide easy-to-use and powerful software stacks.

Bluetooth has already existed for almost 20 years and is used today in approximately 8.2 billion devices, so it has already demonstrated its robustness and dependability. To fulfill requirements set forth by the new IoT scene, the Bluetooth SIG announced the Bluetooth 5 specification in December 2016. The latest Bluetooth standard improves bandwidth, range, broadcasting, and coexistence features.

2x Speed

One of the major features in Bluetooth 5 is a new 2 Mbps PHY. Bluetooth 4.x devices only support a single 1 Mbps PHY rate, but Bluetooth 5 devices are capable of supporting either the 1 Mbps or 2 Mbps PHY rates. By doubling the PHY rate, the amount of data that devices can transfer is almost doubled as shown in the table below. Another benefit of the faster PHY is the reduced time required for transmitting and receiving data, which translates to a lower average current consumption. This is explained by the fact that more time can be spent in low-power sleep modes.

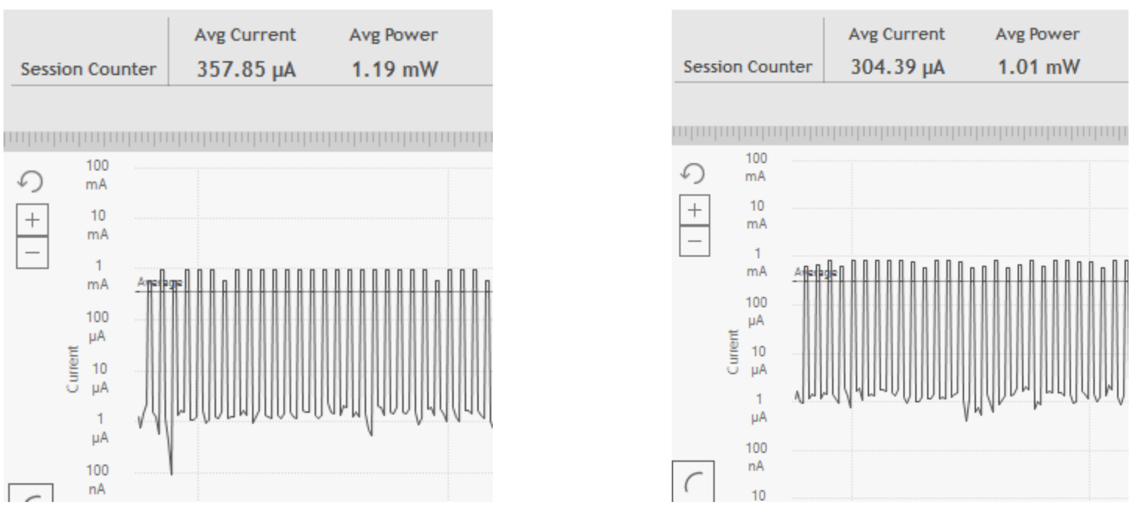
Comparison of 1M and 2M Bluetooth low energy PHYs

PHY	Symbol rate	Error detection	Range multiplier	PDU Length	Minimum packet time	Maximum packet time	Maximum throughput
1M	1 M symbols/s	CRC	1 x	0 - 257 B	80 µs	2.12 ms	800 kbps
2M	1 M symbols/s	CRC	0.8 x	0 - 257 B	44 µs	1.064 ms	1438 kbps

***Note**: Range multiplier value is an approximation*

Doubling the throughput while providing low-power consumption will allow applications to provide faster data transfers for use cases like over-the-air (OTA) firmware upgrades or transmitting of days' worth of collected data from a sensor and also improve latency and responsiveness for time critical applications such as medical devices and security systems.

Bluetooth 5 devices supporting 2 Mbps PHY are still fully backwards compatible with Bluetooth 4 devices and will use the 1 Mbps PHY to communicate with devices that do not support the new 2 Mbps PHY. It is expected that the first smart phones and tablets supporting Bluetooth 5 and 2 Mbps PHY should appear in the market in 2017 and that the majority of smart phones in the market will be Bluetooth 5 compliant within the next two to four years.



Mbps PHY (left) and 2 Mbps PHY (right) average power consumption comparison on EFR32BG12 SoC

The images above show the average current consumption difference between 1 Mbps PHY and 2 Mbps PHY connections measured between two EFR32 Blue Gecko SoCs. The devices used +8 dBm TX power, 25 ms connection interval, and were only sending the shortest 80 µs and 44 µs packets, which provides the least amout of power saving. Even so, the 2 Mbps PHY provides about 15 percent reduction to average power consumption. When using the full length Bluetooth packets and 2M PHY, power savings of up to 40-50 percent should be achievable.

4x Range

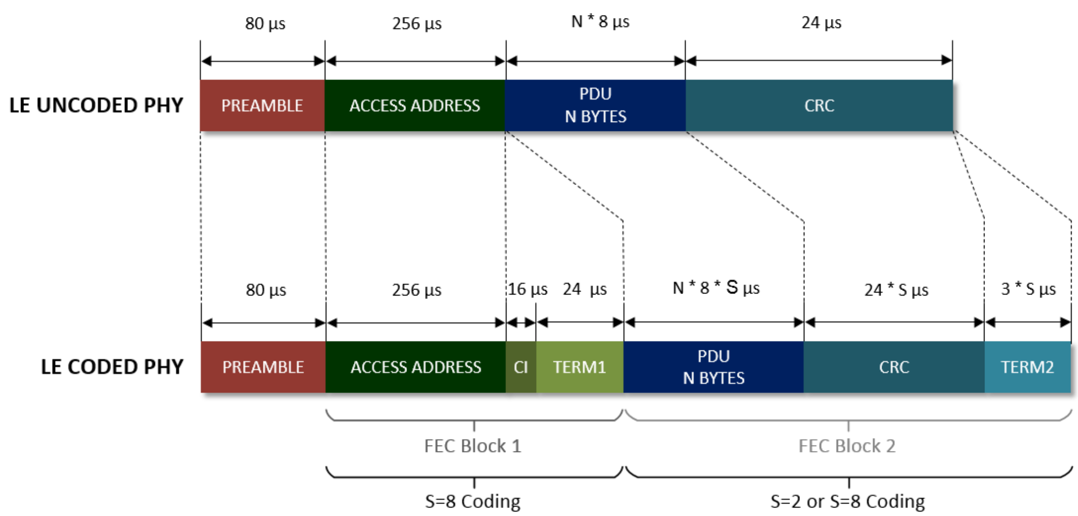
The LE long range feature of Bluetooth 5 can quadruple the range and deliver robust and reliable connections. This means that whole-house and building coverage, as well as new use cases for outdoor, industrial, and commercial applications will become a reality. Those are something Bluetooth has not been able to address earlier, or when it has, the range has been limited.

So how can Bluetooth 5 provide 4x the range?

LE Codec PHY's

In addition to the 2M PHY, Bluetooth 5 contains two additional optional PHYs called LE Coded PHYs. The LE Coded PHYs actually use the 1M PHY rate, but the actual payload is coded either with 500 kbps (S=2) or 125 kbps (S=8) rate, whereas the preamble and access address use the 1M coding.

LE Coded PHY's also use a slightly different packet format versus the 1M and 2M PHYs. A coding indicator (CI) and TERM1 and TERM2 headers are added into the LE packet.



Bluetooth 5 un-coded vs. coded PHY packet format

Using the coded PHYs improves the RX sensitivity, which also means improved range. Typically, a 4-6 dB RX sensitivity improvement can be achieved using either the 500 kbps or 125 kbps PHY and this usually converts to a 2-4x range improvement. The downside of the LE Coded PHY is of course that the TX and RX times are going to be longer, which increases the average power consumption. The table below summarizes the key parameters of LE Coded PHY's.

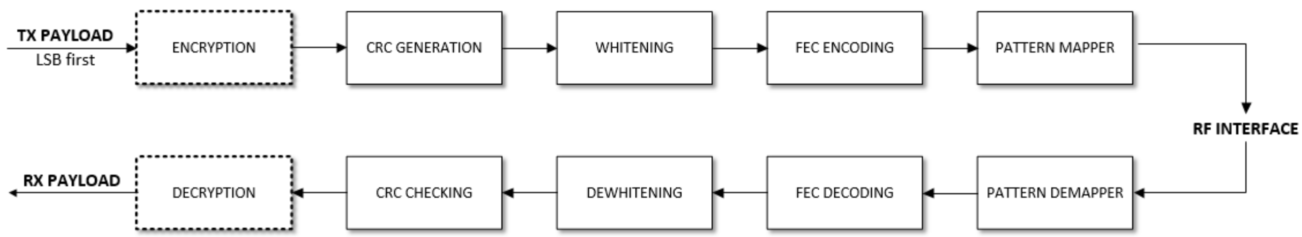
Comparison of LE Coded PHY's

LE Coded PHY	Symbol rate	Error detection	Error correction	Range multiplier	PDU Length	Minimum packet time	Maximum packet time	Maximum throughput
500 kbps S=2	1 M symbols/s	CRC	FEC	2	0 – 257 B	720 µs	17040 µs	382 kbps
125 kbps S=8	1 M symbols/s	CRC	FEC	4	0 – 257 B	462 µs	4542 µs	112 kbps

***Note**: Range multiplier value is an approximation*

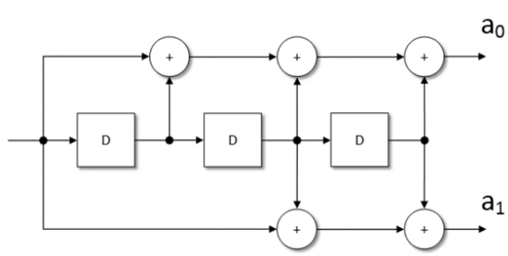
Forward Error Correction and Pattern Mapper

LE Coded PHYs also change the bit stream processing for TX and RX operations, and add two steps into the packet transmissions and reception. First of all, forward error correction is applied to the packet so that the receiver has a capability to correct bit errors upon reception of the packet and improve packet error rate. Secondly, a pattern mapper is applied to the packet to improve the efficiency of the communications. The figure below shows the new bit stream PDU processing sequence.



LE Coded PHY TX and RX packet processing

The FEC block converts each input bit to two output bits by convolutional error correction encoder as shown below, which means the number of bits transmitted is duplicated when FEC is applied to the packet.



FEC encoder

Bits from the convolutional FEC encoder are converted into P symbols in the pattern mapper. P value depends on the selected coding scheme. With S=2 the value of P=1 but if S=8 each bit from the FEC encoder gives four output bits (P=4) as indicated in the table below.

Pattern Mapper output options

Input from FEC Encoder	Output S=2	Output S=8
0	0	0011
1	1	1100

When using S=2, wireless range is roughly doubled with S=8 quadrupled. The downside of the increased range is the burden on the payload created by the added bits required by the FEC algorithm. In effect, with S=2 there is no change (P=1) but with S=8 each bit from the FEC encoder will produce four output bits (P=4). Now the S=2 range will be approximately doubled and S=4 approximately quadrupled. The downside is the additionally required data for FEC algorithm at the receiver end effects the amount of data to be transmitted, thus reducing the data rate correspondingly. The net effect of the FEC encoder and the pattern mapper is that one bit becomes two bits with S=2 and eight bits with S=8.

Maximum Transmit Power and Channel Selection Algorithm #2

Maximum transmit power in Bluetooth 5 is defined to be +20 dBm, while in the Bluetooth 4 specification this level was defined at +10 dBm. Increasing the TX power by 10x of course can have a radical impact to the maximum range.

Using a +20 dBm TX power with Bluetooth low energy technology is however not that straightforward because different regulatory bodies do not allow transmit powers higher than 10 dBm due to the simplified hopping sequence and the small number of channels Bluetooth with low energy radios can use while advertising or in a connection. However, the Bluetooth 5 specification includes enhancements to both advertising and channel selection algorithms that make it possible to use more RF channels than Bluetooth 4. These enhancements may allow Bluetooth 5 devices to use higher than +10 dBm transmit power globally in the future, improving range and creating more robust connections. One of the new features is Channel Selection Algorithm #2 (CSA#2) and it both improves the interference tolerance of the Bluetooth radio as well allows the radio to limit the minimum number of RF channels the radio can use in high interference environments. When limiting the minimum number of channels to 15 it should be possible to increase the TX power above the +10 dBm limit.

Impact to Range

The simplest way to approximate the theoretical range for radios is to use the free space loss formula:

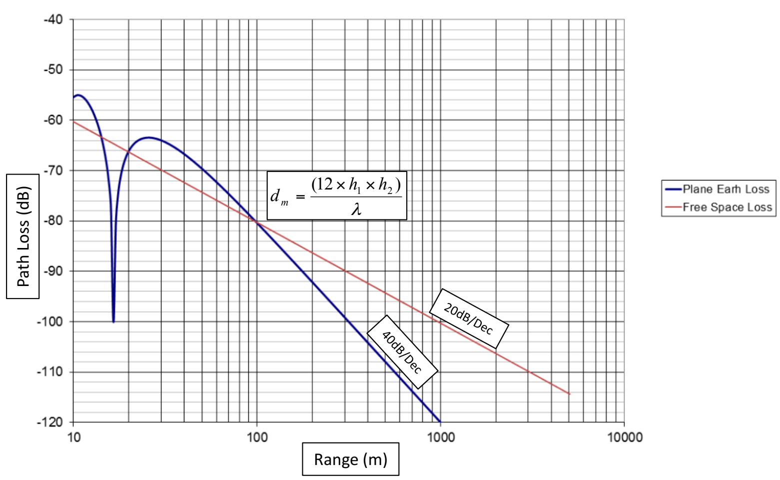
$$L_P(dB) = 92{,}45 + 20\log F + 20\log D$$

F is the frequency in GHz and D is the distance in kilometers. This formula however doesn't take into account the losses caused by multipath propagation (reflections) nor the antenna loss and thus often results in too optimistic approximations.

To have a more realistic approximation of the range, one can assume an open field with antennas which are *h* meters above ground and calculate the range which takes into account the antenna loss and reflection from the ground. This approximation will give a very accurate estimate of the range in an open field, like an airfield for example. The plane earth loss can be calculated using the following formula:

$$\frac{P_R}{P_T} = 2\left(\frac{\lambda}{4\pi r}\right)^2\left[1-\cos\left(k\frac{2h_1 h_2}{r}\right)\right]$$

Where h_1 and h_1 are the height of the antennas respectively, *k* is the free space wavenumber and *r* is the distance between the antennas. The difference between free space loss and the plane earth loss is plotted in to the following figure:



Free space loss vs. plane earth loss

To simplify this even further, one can estimate a 20 dB/decade loss until distance of d_m and 40 dB/decade beyond that. Thus we get the following formula:

$$d_m = \frac{(12 \times h_1 \times h_2)}{\lambda}$$

In the formula above h_1 and h_2 are the height of the antennas above ground. Placing the antennas higher will move the distance d_m further, thus increasing the range and vice versa.

With a typical Bluetooth application, the direction where the remote end of the link is located is not well specified and thus the gain of the antenna is not relevant in approximating the range. Antenna efficiency is a number which describes the total amount of RF energy radiated into the air compared to the RF energy fed into the antenna. The efficiency thus gives a better approximation of the average range regardless of the positions of the device. With an optimal antenna design it is possible to achieve a -1dB antenna efficiency. In practice, the antenna performance depends greatly on the PCB and mechanical design around the antenna. Typical efficiency with a good antenna design is -5 dB. The physical size of an antenna and the size of the PCB design also has an impact on antenna efficiency in practice and with very small designs in which antenna efficiency is not more than -8 dB.

Estimated maximum ranges for EFR32BG12 with different TX power and RX sensitivity levels

TX Power	RX sensitivity	Antenna efficiency	Link budget	Maximum range in open field	Use case
0 dBm	-92 dBm	-5 dBm	82 dBm	160 m	EFR32BG12, 0 dBm, 2 Mbps PHY sensitivity
0 dBm	-95 dBm	-5 dBm	85 dBm	195 m	EFR32BG12, 0 dBm, 1 Mbps PHY sensitivity
10 dBm	-92 dBm	-5 dBm	92 dBm	295 m	EFR32BG12, 10 dBm, 2 Mbps PHY sensitivity
10 dBm	-95 dBm	-5 dBm	95 dBm	350 m	EFR32BG12, 10d Bm, 1 Mbps PHY sensitivity
20 dBm	-92 dBm	-5 dBm	102 dBm	530 m	EFR32BG12, 20 dBm, 2 Mbps PHY sensitivity
20 dBm	-95 dBm	-5 dBm	105 dBm	630 m	EFR32BG12, 20 dBm, 1 Mbps PHY sensitivity

Note: Assumes a typical design with -5dB antenna loss and antennas placed 1.5 meters above the ground. Estimated between two EFR32BG12s.

8x Advertising Capacity

Beacons are small Bluetooth transmitters that can send data to any other Bluetooth low energy technology-enabled devices such as smart phones and tablets within their range. Beacons make it possible to push short messages to those devices and enable simple communications with them. Today bacons are typically used for retail advertising, indoor positioning, and asset tracking. Beaconing has quickly become one of the most successful use cases for Bluetooth and it is estimated to continue growing at a fast rate. Analysts expect more than 500 million beacons to be shipped by 2021.

One of the major areas of improvement in the Bluetooth 5 specification is how Bluetooth advertisement (beaconing) works and the new specification contains significant updates to beaconing capabilities compared to previous versions of the specification. These improvements will not just allow much more advanced and intelligent beacons to be developed but also completely new use cases and applications such as unidirectional data streaming over Bluetooth advertisements.

A brief introduction to the most important changes to the Bluetooth advertisement capabilities is provided below.

Advertising Data Sets and Scan Request Event Reporting

One of the basic improvements in Bluetooth 5 advertising is the Advertising Data Sets feature, which allows a single Bluetooth 5 device to send out multiple individual advertisement data sets with unique intervals and advertisement data. This, for example, enables a single Bluetooth beacon to transmit individual Apple iBeacon and Google Eddystone beacons simultaneously.

A Bluetooth 5 compatible advertiser can also now detect when a scan request is made by a remote device and report the request to the application level. The application can use this to detect a remote device has received one of the advertisement packets it has sent out. This is helpful in several ways, including reducing power consumption since the advertiser will be able to detect that the remote device has received the sent advertisement packet and can stop advertisement.

Secondary Advertisement Channels

Bluetooth 4 devices use three advertisement channels to advertise their presence, open connections, or broadcast data. The payload in a single advertisement packet is limited to 31 bytes. A single 128-bit service UUID can consume most of the advertisement payload and for some applications like advanced beacons this is a limitation.

Bluetooth 5 changes this significantly. First of all, the three advertisement channels are going to remain exactly like in Bluetooth 4 for backwards compatibility and interoperability, but they are now called primary advertisement channels. In addition to the three primary advertisement channels, Bluetooth 5 devices can use any of the remaining 37 data channels as secondary advertisement channels to broadcast more data and offload the primary channels. The table below summarizes the differences between Bluetooth 4 and 5 advertising channel schemes.

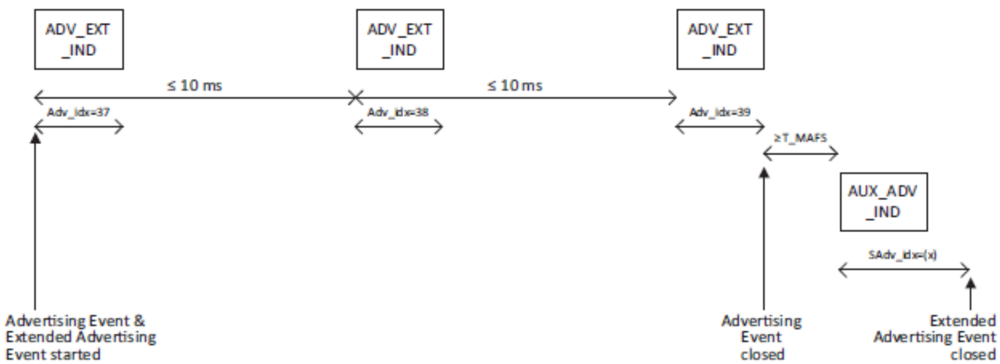
Advertising channels in Bluetooth 4 vs Bluetooth 5

Bluetooth version	Advertising channels	Payload	PHY
Bluetooth 4	3	0 - 31 B	1M
Bluetooth 5	3 Primary 37 Secondary	0 - 31 B (Primary) 0 – 255 B (Secondary)	1M, Coded (Primary) 1M, 2M, Coded (Secondary)

Secondary Advertising Packets

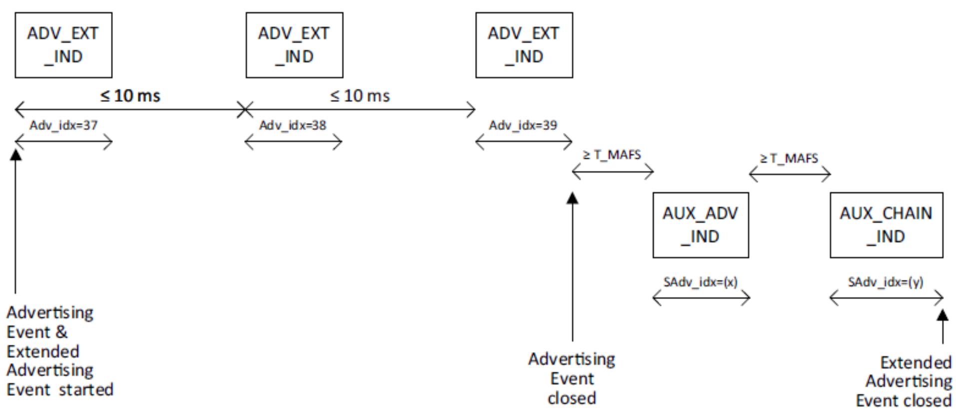
In addition to the new advertisement channels, Bluetooth 5 also introduces a new advertisement packet type called ADV_EXT_IND. This packet can be sent on the primary advertisement channels and it indicates additional data will be available through a secondary advertisement. The ADV_EXT_IND packet contains information about the secondary advertisement such as on which channel the advertisement occurs, when it occurs, and which Bluetooth PHY will be used.

In the simplest use case, an AUX_ADV_IND packet is sent on the secondary advertisement channel containing an additional advertisement payload as shown in the example below. The AUX_ADV_IND packet can contain payload up to 255 bytes.



Advertising event using the ADV_EXT_IND PDUs and AUX_ADV_IND PDU containing advertising data

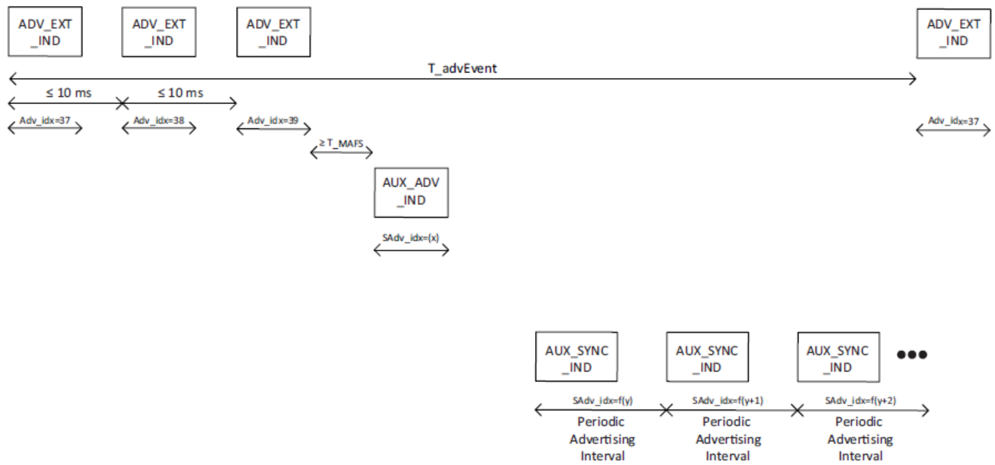
In case the advertiser wants to send more data than a single AUX_ADV_IND packet can contain, it is possible to chain multiple secondary advertisements using the AUX_CHAIN_IND packet as shown in the image below. AUX_CHAIN_IND packets can also contain pointers to additional AUX_CHAIN_IND packets in order to transmit advertisement payloads beyond 255 bytes.



Providing additional advertisement data using AUX_CHAIN_IND

Periodic Advertising

Yet another improvement to the Bluetooth 5 advertisement capabilities is a mode called Periodic Advertising. As the name suggests, periodic advertising enables the advertiser to send out changing advertisement data periodically and with a fixed interval, and one or multiple scanners can listen to it. Periodic advertisement mode is indicated with the ADV_EXT_IND packets, which point to AUX_ADV_IND packet, containing the actual information about the periodic advertisement mode, such as interval, hopping sequence, advertiser address, and so on. The advertiser will also send AUX_SYNC_IND packets at the identified interval containing the actual periodic advertisement data.



Periodic advertising

The advertiser will periodically send new ADV_EXT_IND packets, so that new scanners can synchronize to the data stream or existing scanners can resume a lost sync.

Summary of Bluetooth 5 advertising channel PDUs

Activity	PDU name	Allowed LE PHYs			Advertising channel
		1M	2M	Coded	
Connectable and scannable undirected advertising	ADV_IND	Yes			Primary
Connectable directed advertising	ADV_DIRECT_IND	Yes			Primary
Non-connectable and non-scannable undirected advertising	ADV_NONCONN_IND	Yes			Primary
Scan request	SCAN_REQ	Yes			Primary
Scan request	AUX_SCAN_REQ	Yes	Yes	Yes	Secondary
Scan response	SCAN_RSP	Yes			Primary
Connection request	CONNECT_IND	Yes			Primary
Connection request	AUX_CONNECT_REQ	Yes	Yes	Yes	Secondary
Scannable undirected advertising	ADV_SCAN_IND	Yes			Primary
All advertising events (except connectable and scannable undirected)	ADV_EXT_IND	Yes		Yes	Primary
All advertising events (except connectable and scannable undirected)	AUX_ADV_IND	Yes	Yes	Yes	Secondary
AUX scan response	AUX_SCAN_RSP	Yes	Yes	Yes	Secondary
Periodic advertising	AUX_SYNC_IND	Yes	Yes	Yes	Secondary
Additional advertising data	AUX_CHAIN_IND	Yes	Yes	Yes	Secondary
Connection response	AUX_CONNECT_RSP	Yes	Yes	Yes	Secondary

Bluetooth 5 Support on Phones and Tablets

The first Bluetooth 5 enabled phones and tablets are expected to arrive on the market during 2017 and typically it has taken 2-4 years after a new Bluetooth specification release for the majority of the phones on the market to support the new standard. At the time of this writing the first phone on the market with Bluetooth 5 support is the Samsung Galaxy S8, which supports the Bluetooth LE 2M PHY. As the new features, with the exception of the errata in the Bluetooth 5 specification, are optional, it is always recommended to consult the manufacturer or understand which of the Bluetooth 5 features are supported by a particular device.

Summary

Bluetooth 5 contains improvements and new features which place this robust and proven wireless standard ahead of the game just as the industry starts the race towards the age of IoT in earnest. The improvements introduced in Bluetooth 5 enable the continued and increasing use of Bluetooth devices in evolving smart home, medical, wearable, automotive, beaconing, location, and many other IoT applications.

Silicon Labs has already launched the first Bluetooth 5 compatible EFR32 Blue Gecko SoC already supporting the Bluetooth LE 2M PHY and some of the advertisement enhancements. More information and more detailed specifications of the Blue Gecko SoCs and modules can be found from http://www.silabs.com/bluegecko.

References

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Bluetooth Core Specification V 5