RUTRONIK
ELECTRONICS WORLDWIDE

Whitepaper

Bluetooth® 5

Determination of practical extremes of Bluetooth Low Energy:

Throughput, energy consumption and maximum range

Abstract:

This white paper focuses on an experimental performance evaluation of the Bluetooth Low Energy Technology Version 5. The main objective of this work was to experimentally determine the communication range, the data throughput and the energy consumption of Bluetooth 5 and Bluetooth 4. Different data packet sizes, different transmission powers, coded and uncoded physical layers (in the following: PHY) as well as different connection parameters were configured. The measurement results obtained using the Nordic Semiconductor nRF52840 chip are representative of indoor and outdoor cases. The results show the practical communication range, the data throughput and the energy consumption of the Bluetooth 5 connection and give an insight into the possible new areas of application. In addition, the measurement results show that different connection parameters have a major impact on data throughput and thus an impact on energy consumption. The experiment will draw conclusions about the possible new application areas of Bluetooth Low Energy and record the measurement results for customer service.

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1 Introduction

In recent years, mobile devices have gained in importance across all areas due to more powerful battery technologies, more efficient computing devices, and new wireless communication technologies. The smartphone has evolved into the control center of not only these mobile devices, but it also serves to interact and exchange information with other people and machines across borders. Most of the time, these devices use the 2.4 GHz license-free band to transfer data across various wireless technologies including ANT, Bluetooth, Thread, Gazel, and Zigbee. They are mostly used for energy-sensitive and cost-sensitive applications and can be operated with button cells for several months to years. Because of this property, they are used, for example, in industrial, home automation, sports and medical fields. Despite the competition from other ISM radio bands and interference / coexistence challenges, Bluetooth has become the standard technology and has undergone continuous improvements since its introduction in the 1990s. The Low Energy version of Bluetooth Low Energy, from Bluetooth 4.0, was released in June 2010 and can be found today in almost every smartphone, tablet and laptop, as well as in several wireless devices (1). The latest version, Bluetooth 5, was released in December 2016 (2) with the first commercial development kits released in early 2017. The first smartphone to support Bluetooth 5 is the Samsung Galaxy S8 (3). However, it lacks support for the long-range LE coded mode. The wide range of functionalities has made Bluetooth useful in Internet of Things (IoT) applications. The official announcement of Bluetooth 5 indicates that the range is quadrupled compared to Bluetooth 4.2 (4). Even after extensive research, the available literature provides no information about the practical performance of Bluetooth 5. This work aims at using measurements to evaluate the performance of Bluetooth 5 and to make the findings available to Rutronik Elektronische Bauelemente GmbH in the form of a white paper.

Furthermore, Chapter 2 describes the performance characteristics of the Bluetooth 5 technology in summary. This is followed by Chapter 3 with the factors influencing range, throughput and power consumption. Chapter 4 first describes the test setup, and then explains the indoor and outdoor measurements. The evaluation of the measurement results is discussed in chapter 5. A summary of the measurement results and an outlook and suggestions for future measurements to more accurately determine the performance of the technology are provided in Chapter 6.

1.1 Important hint about the used pre-production version

We would like to point out that subsequent work has been performed with both a hardware prototype and a software prototype.

The expected results for today's production-ready chips and software stacks are considerably higher.

2 Performance characteristics of Bluetooth 5 technology

Bluetooth 5 is a further development of Bluetooth low-energy technology, which greatly improves the performance of the previous version. In addition to minor optimizations, the improvements mainly relate to the range, data throughput and functionality of the transmission modes. This section focuses on the new functionality of Bluetooth 5 compared to the previous version 4.2.

Improvements in communication range and maximum throughput have been achieved in the Bluetooth 5 specification with the introduction of three new Physical Layer (PHY) options. In addition to the 1 Mbps wireless frequency hopping rate (FHSS) of Bluetooth Low Energy 4.2, Bluetooth 5 specifies two additional transmission rates: On the one hand 2 Mbit / s PHY, referred to as LE 2M, for short range and high speed (high-speed mode), on the other hand two coded PHY, referred to as LE Coded, which provides the gross data at 500 Kbps or 125 Kbps transfers. The LE Coded PHYs are coded in two stages: first by "Forward Error Correction convolutional encoder" and then by "Pattern Mapper". In theory, this allows the link budget of LE-coded transmissions to increase more than 6 dB and 12 dB compared to LE 1M (5). It should be noted that only support for LE 1M is backwards compatible with Bluetooth Low Energy up to version 4.0. In addition to both other transmission rates, AE (Advertising Length Extension) has been added to Bluetooth 5 for optional use. The concept of secondary channels is also an innovation. This allows the use of data channels even in advertising processes. The format of the advertising packages used in the secondary channels has been revised to 255 bytes (6).

Bluetooth 5 is backwards compatible with the earlier versions of BLE. The innovations described above are optional and must be activated specifically. The range or the data rate could be increased with the new feature, which makes communication with older Bluetooth devices impossible. With the new features, only the range or the data rate can be increased. The Bluetooth SIG claims that Bluetooth 5 quadruples reach and advertise packets grow eightfold (in terms of broadcast); this is twice the speed compared to Bluetooth 4.0. However, the improved range and data rate cannot be achieved simultaneously because different transmission modes are used. Table 1 summarizes the features of Bluetooth 5.

Table 1: Summary of the Bluetooth 5 characteristic

PHY	Error Control	Range multiplier	PDU Length
1 M	CRC	1 x	0 – 257 Bytes
2 M	CRC	0,8 x	0 – 257 Bytes
Coded, S = 2	CRC and FEC	2 x	0 – 257 Bytes
Coded, S = 8	CRC and FEC	4 x	0 – 257 Bytes

3 Factors

This section describes the parameters that could influence the experiment.These affect range, throughput, and then energy consumption.

3.1 Factors influencing the range

To determine the maximum range of Bluetooth Low Energy, it is helpful to understand which parameters limit these. These include the frequency band used to transmit the data, transmit power and environmental conditions. The following points will discuss these factors in more detail.

- frequencies

One major aspect of Bluetooth's low range is the strong attenuation of high-frequency waves. Bluetooth Low Energy uses frequencies between 2400 and 2480 MHz. These are also used by many other wireless technologies such as IEEE 802.15.4, ANT +, Thread and proprietary protocols. This can lead to disturbances and shorter range.

- Transmission power

The low allowable transmit power for Bluetooth Low Energy is also a big challenge when covering a long distance. This is standardized by law and is 100 mW (20 dBm). The maximum configurable transmission power differs depending on the transceiver. Nordic's nRF52840 has a maximum of 4 dBm in normal and high-speed mode and 8 dBm in long-range mode. The higher the transmission power at the same frequency, the greater ranges can be achieved. Also, the reception sensitivity plays a very large role in determining the range. This depends on the mode in which the device is located. In Long Range mode this is -103 dBm in long-range mode (LE Coded PHY 125 kbps), -92 dBm in high-speed mode (LE 2M) and -93 dBm in normal mode (LE 1M) for the chip used in the Frame of this work.

- Environmental conditions

The environment in which the devices are operated to carry out the experiment also has an impact on the range. In buildings, the range is usually limited by walls and ceilings. The material has a major impact on how much the signal is attenuated. Indoors, these obstacles can be concrete walls, for example, which attenuate the signal accordingly more than lightweight walls, shelves, people, furniture or other, less thick obstacles.

Outdoors, a BLE connection could operate for up to one kilometer with the line of sight of the receiving device. Even outdoors, obstacles such as trees will negatively affect the range. In addition, there are weather conditions such as rain or snow, which also affect the range.

The importance of the Fresnel zone lies in the fact that, due to the wave character, the propagation of the electromagnetic radiation through obstacles can be disturbed, even if there is visual contact between the transmitting and receiving antenna. It starts and ends at the respective antennas and should be free from the obstacles.

The Fresnel zone is shown in Figure 1. The Fresnel zone is widest in the middle between the two antennas. The obstacles in the Fresnel zone could affect the range of Bluetooth in the measurements.

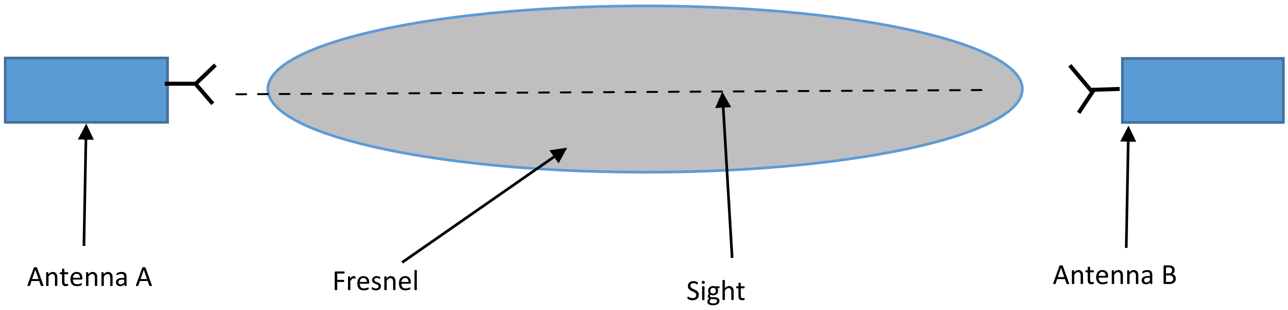


Figure 1:Fesnelzone

3.2 Factors influencing the data throughput

1 Megasymbol/s and 2 Megasymbols/s are the modulation frequencies that Bluetooth5 Low Energy uses to transmit the data. The data throughput determines the net amount of data per second which can be transmitted. The following parameters influence or limit the data throughput of Bluetooth Low Energy:

- connection interval

The connection interval effectively determines how many packets can be transmitted within a connection event. The maximum allowable connection interval for the Nordic nRF51 and nRF52 is between 7.5 ms and 400 ms. The higher the value; the more packets can be transmitted in one connection event.

- interference

If there is interference and the first connection event is not received correctly, the connection event is terminated and the data must be resent in the next connection event. If the last package is disturbed, the impact is less; the first package must wait for the entire configured connection interval. This can be configured with the Nordic stack: from 7.5 ms to 400 ms.

- Inter-frame Space (IFS)

The IFS denotes the time interval between two consecutive packets. This is 150 µs and has to be transferred with every Bluetooth low-energy package. Figure 2 shows the IFS within one connection interval, where "T" is the transmission packet and "R" is the reception packet.

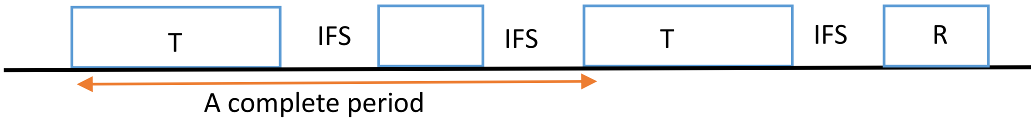


Figure 2: Connection interval with IFS

- The size of pacts

ATT-MTU (Maximum Transmission Unit) determines the maximum amount of data that can be processed by sender and receiver and stored in their buffers. The ATT MTU value affects the amount of overhead data. There is no limit to the specification of how high the ATT MTU value can be, but the Bluetooth stack used may have its limitations.

This will be described in more detail in the next section.

3.3 Factors influencing energy consumption

The main factors that affect the power consumption of Bluetooth Low Energy are the transmit power and total duration of the radio (Rx and Tx).

The required transmit power depends on how often the radio needs to transmit or receive and the length of time it takes to transmit or receive.

4 Measurement setup and implementation of the experiment

This section describes the test setup as well as the hardware and software used. Afterwards, the implementation of the experiment indoors and outdoors is described in more detail.

4.1 Measurement Setup

The nRF52840 from Nordic Semiconductor was used in this study. This chip is one of the first to support Bluetooth Low Energy Version 5.

NRF52840 is a System On Chip (SoC) that combines the integration of a multi-protocol 2.4 GHz transceiver with an ARM Cortex-M4F-based microcontroller. The chip was programmed with the soft device s140 v6.0.0-6 (alpha). This is a precompiled stack of Nordic, which contains the Bluetooth low-energy protocol. This softdevice version is an alpha version and only supports some of the Bluetooth features.Two Preview Development Kits (PDK) were used for the experiment. The Power Profiler Kit (PPK) was connected to a kit via the GPIO. This kit was then connected to a computer running the measurement software. PPK is a powerful and flexible tool developed by Nordic Semiconductor to measure power consumption in real time. Figure 1 shows the test setup with the hardware used.

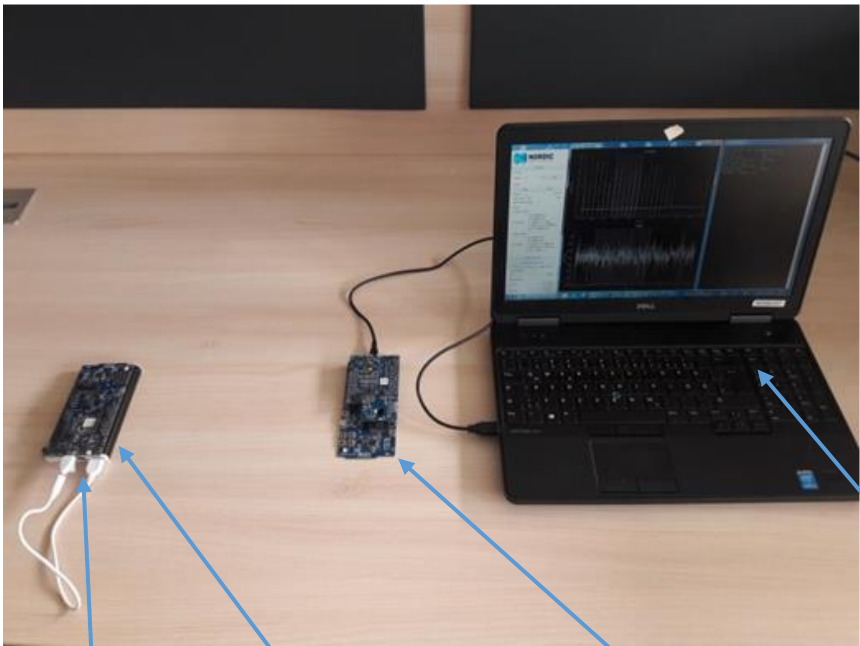


Figure 3: Measurement setup and used devices

The firmware for this work is based on the ATT_MTU throughput example from the nRF52 Software Development Kit (SDK) V14.2.0-1.

When the firmware is running, both devices first use an LE 1M in the advertising process to "discover," connect, and configure the desired connection parameters. These connection parameters are:

- ATT_MTU: the abbreviation stands for Attribute Protocol Maximum Transmission Unit and defines the maximum data packet size of the attribute protocol. The ATT_MTU is defined on the L2CAP layer and can be configured between 23 and 247 bytes. Figure 2 shows the structure of the ATT packet, where the opcode includes the ATT operations such as write command, notification, read response, and so forth. The ATT data field contains the application data.

Figure 4: Structure of an ATT package

When sending a write, read, notification or display packet, the corresponding attribute handle for identifying the data must also be included. This attribute handle is 2 bytes. Figure 3 shows an ATT package with attribute handle.

Figure 5: ATT package with attributes handle

- Connection interval: Connection interval defines in milliseconds how often the devices must hear in receive mode. If this value is increased, more packets can be transmitted in one interval.

- Data Lenth Extension (DLE): the standard data length for a radio packet is 27 bytes. The DLE allows you to use larger wireless packets so that more data can be sent in one packet.

- Physical Layer (PHY) data Rate: this allows to configure the transmission rate (LE 1M, LE 2M and 125 Kbps LE coded).

For this experiment, the firmware and hardware have been modified. First, the configuration parameters were extended by the adjustable transmission power. Then, for current measurement, the SB40 shorting bar was disconnected to connect P22 in series with the load. In this case, the kit can no longer be programmed. To bring the development kit into normal operation, the shorting bridge was soldered.

It should be noted that at the time of the experiment support for the Bluetooth 5 functionality of the nRF52840 chipset was limited. This limitation relates inter alia to the transmission rate; LE 2M and

125 kbit/ s LE Coded were only available in data channels. Previously, the connection with LE 1M had to be established for data transmission. This limitation was noted in the first measurements. The devices were placed 20 meters apart to configure the desired maximum range parameters and establish a Bluetooth low energy connection between the two devices.

One device was placed at a fixed point; the other one was farther and farther away until the connection broke off. The point at which the connection broke determines the maximum range. At this point, it was no longer possible to establish a connection between the two devices, since LE 1M, which is needed to establish a connection, cannot bridge. In later versions of the stack, according to the manufacturer, it will also be possible to set up long-range parameters.

4.2 Carrying out the experiment

4.2.1 Indoor measurements

The measurements were carried out on the first floor of the company Rutronik, Industriestraße 9, in Ispringen. It is a drywall with 12 cm wall thickness. A total of 2 measurement scenarios were carried out.The first scenario with Bluetooth 4.2 and 10 series measurements, where five were performed with 0dBm and five with 4dBm. The second scenario was carried out with Bluetooth 5.0 in high-speed mode; here also 10 series of measurements were carried out, each with 5 for 0dBm and 4dBm. Subsequently, further series of measurements were carried out to determine the range in long-range mode. Figure 4 gives an overview of the indoor measurement results.

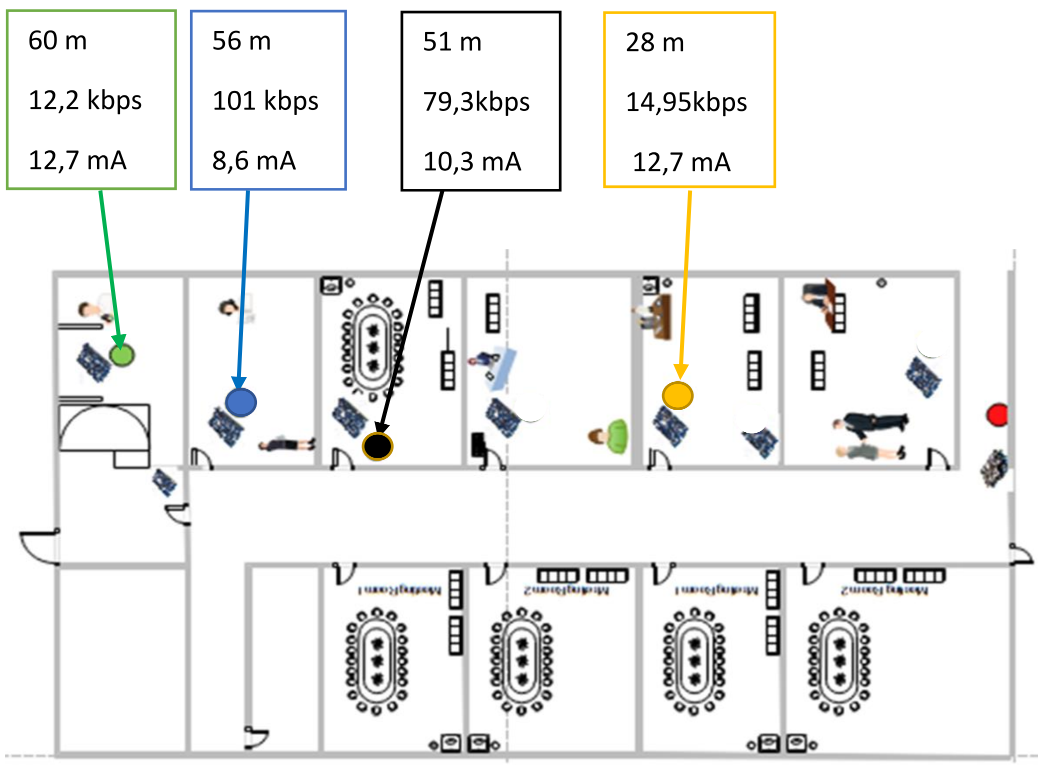


Figure 6: Indoor measurement results

- First measurement scenario

In the first scenario, the data was transmitted with 0 dBm transmission power and performed 10 different measurement series. For the first measurement series, LE PHY 1M was configured for data transfer (BLE 4.2), the ATT_MTU packets were set to 23 bytes, the DLE disabled and the minimum connection interval set. At a distance of one meter, a connection between the two devices was made with no physical interference and transmitted 1024 kB. The result: power consumption of 11.42 mA, throughput of 209.5 Kbps and 40.5 seconds for transmission. Then a device was removed further and the data sent again. The distance was increased until no connection between the two devices was possible. The fixed device was connected to the computer. On this device, the notifications could be received and the connection parameters configured. The other device received only the data packets. A throughput of 37.4kbps and 9.02mA was measured at a maximum range of 44 meters. Thus it can be stated that the power consumption at 44 meters was increased by a factor of 1.266. Table 2 summarizes the measurement results of the first measurement series again.

Table 2: Measurement result of the first measurement series with Bluetooth 4.2

1. scenario	
1. measurement series	
Max distance	**44m**
data rate	1 Mbps
ATT_MTU	23 Bytes
transmission power	0 dBm
connect-Intervall	7.5 ms
DLE	OFF
Time to transfer	**224,4 s**
throughput	**37,4 kbps**
power consumption	**9,02 mA**

In the second series of measurements, the length of the ATT_MTU was set between the minimum and the maximum, namely 158 bytes. The connection interval was set to 50ms, the DLE enabled, and the raw data rate was consistent at 1 Mbps. At a distance of one meter, a throughput of 775.3 kbps was measured. The power consumption was 13.09 mA and it took 11.4 s to transmit 1 megabit.Compared to the previous series of measurements, the throughput increased by a factor of 4 at a distance of one meter. Also to be observed was the power consumption, which had increased by 1.67 mA. At the same time, the time required to transmit the data decreased by about a factor of 4.

Although it was still possible to establish a connection at a distance of 53 meters, not all data could be transmitted due to constant disconnections. At a distance of 51 meters, a stable connection could be established. This corresponds to the black dot in Figure 4. A throughput of 80.7 kbps, a power consumption of 8.3 mA and 104 s for the transmission of the data packets could be achieved. The configuration parameters and the measurement results of the second measurement series are shown in Table 3.

Table 3: Measurement result of the second measurement series with Bluetooth 4.2

1. scenario	
2. measurement series	
Max distance	**51 m**
data rate	1 Mbps
ATT_MTU	158 Bytes
transmission power	0 dBm
connect-Intervall	50 ms
DLE	ON
Time to transfer	**104 s**
throughput	**80,7 kbps**
power consumption	**8,3 mA**

In the third series of measurements, the maximum configurable ATT_MTU packet (247 bytes) was configured with a connection interval of 50 ms and the DLE remained active. At a distance of one meter, a throughput of 907.2 kbps, a power consumption of 13.50 mA and 9.2 s for the transmission of data was measured. As in the second series of measurements, a maximum range of 51 meters was achieved. A throughput of 73.5 kbps, a power consumption of 6.3mA and 114.5s for the transmission of the total amount of data was measured. The measurement results from the third series of measurements are summarized in Table 4. Compared to the second series of measurements, 2 mA was saved and a throughput of 7.2 kbps was lost. The configuration parameters and the measurement results of the third measurement series are summarized in Table 4.

Table 4: Measurement result of the third series of measurements with Bluetooth 4.2

1. scenario	
3. measurement series	
Max distance	**51 m**
data rate	1 Mbps
ATT_MTU	247 Bytes
transmission power	0 dBm
connect-Intervall	50 ms
DLE	ON
Time to transfer	**114,5 s**
throughput	**73,5 kbps**
power consumption	**6,3 mA**

The fourth series of measurements is almost identical to the third. Only the DLE has been deactivated. At a distance of one meter, it can be surprisingly found that a data rate of 257.1 kbps, a power consumption of 11.6 mA and 36.6 s were measured.

The deviations of the measured values are small compared to the first measurement series, although the ATT_MTU packet size has been set to maximum. A maximum range of 51 meters with 22.5 kbps data rate, a power consumption of 8 mA and duration of 372.4 s was achieved. It should also be noted that the total amount of data needed significantly more time to be transferred.

Table 5: Measurement result of the fourth series of measurements with Bluetooth 4.2

1. scenario	
4. measurement series	
Max distance	**51 m**
data rate	1 Mbps
ATT_MTU	247 Bytes
transmission power	0 dBm
connect-Intervall	50 ms
DLE	OFF
Time to transfer	**372,4 s**
throughput	**22,5 kbps**
power consumption	**8 mA**

In the fifth series of measurements, the maximum size of the ATT data packet and the maximum connection interval were set. A maximum range of 44 meters was achieved with these parameters. For this purpose, a power consumption of 7.6 Milliamperes, a data rate of 63.8 kbps and 131.6 s was measured for the transmission of the entire data volume. The configuration parameters and the measurement results of the fifth measurement series are summarized in Table 6.

Table 6: Measurement result of the fifth measurement series with Bluetooth 4.2

1. scenario	
5. measurement series	
Max distance	**44 m**
data rate	1 Mbps
ATT_MTU	247 Bytes
transmission power	0 dBm
connect-Intervall	400 ms
DLE	ON
Time to transfer	**136,6 s**
throughput	**63.8 kbps**
power consumption	**7,6 mA**

The measurement series was then repeated with 4 dBm transmission power.

The configuration parameters and the measurement results of the sixth measurement series can be seen in Table 7. A maximum range of 56 meters has been reached. This corresponds to the blue dot in Figure 4. A throughput of 51kbps and a power consumption of 10.1 mA were measured. It took 164 seconds to transfer the amount of data. Comparing this measurement series with the measurement series of the first scenario, one finds that with the increase of the transmit power an additional 12 meters were reached. The throughput has been cut in half.

Table 7: Measurement result of the sixth measurement series with BLE 4.2

1. scenario	
6. measurement series	
Max distance	**56 m**
data rate	1 Mbps
ATT_MTU	27 Bytes
transmission power	4 dBm
connect-Intervall	7,5 ms
DLE	OFF
Time to transfer	**164,5 s**
throughput	**51 kbps**
power consumption	**10,1 mA**

In the seventh series of measurements 53 meters were achieved as the maximum range, with the throughput was 48.9kbps and a current of 10.6 mA was reached. 164.5s was needed to transfer all the data. A connection at 60 meters distance was still possible. However, the total amount of data could not be transmitted because of an unstable connection (disconnection). The configuration parameters and the measurement results of the sixth measurement series are summarized in Table 8.

Table 8: Measurement result of the seventh measurement series with BLE 4.2

1. scenario	
7. measurement series	
Max distance	**53m**
data rate	1 Mbps
ATT_MTU	158 Bytes
transmission power	4 dBm
connect-Intervall	50 ms
DLE	ON
Time to transfer	**171,6 s**
throughput	**48,9 kbps**
power consumption	**10,6 mA**

In the eighth series of measurements, a maximum range of 56 meters was achieved. The throughput is high despite a long distance and is 101 kbps. A current of 8.6 mA was measured and 83.9 seconds were needed to transmit the entire amount of data. The configuration parameters and the measurement results are summarized in Table 9.

Table 9: Measurement result of the eighth measurement series with Bluetooth 4.2

1. scenario	
8. measurement series	
Max distance	**56 m**
data rate	1 Mbps
ATT_MTU	247 Bytes
transmission power	4 dBm
connect-Intervall	50 ms
DLE	ON
Time to transfer	**83,9 s**
throughput	**101,1 kbps**
power consumption	**10,6 mA**

In the ninth series, as in the sixth series, 56 meters were achieved. The time to send the same amount of data is significantly higher and is 397.1 seconds. A data rate of 21.1 kbps and a power consumption of 8.3 mA were measured (see Table 10).

Table 10: Measurement result of the ninth series of measurements with Bluetooth 4.2

1. scenario	
9. measurement series	
Max distance	**56 m**
data rate	1 Mbps
ATT_MTU	247 Bytes
transmission power	4 dBm
connect-Intervall	50 ms
DLE	OFF
Time to transfer	**397,1 s**
throughput	**21,1 kbps**
power consumption	**8,3 mA**

In the tenth series of measurements, a connection could be established at 56 meters. Due to a disconnect, the entire amount of data could not be transferred. Only with a maximum range of 51 meters could a stable connection take place. 239.5 seconds were needed at this distance to transmit all the data. A data rate of 35 kbps and a power consumption of 9.8 mA were measured (see Table 11).

Table 11: Measurement result of the tenth series of measurements with Bluetooth 4.2

1. scenario	
10. measurement series	
Max distance	**56m**
data rate	1 Mbps
ATT_MTU	247 Bytes
transmission power	4 dBm
connect-Intervall	50 ms
DLE	OFF
Time to transfer	**397,1 s**
throughput	**21,1 kbps**
power consumption	**8,3 mA**

- Second measurement scenario

On the one hand, LE 2M was used and, as in the previous scenario, 10 measurement series were carried out. Of these, five measurement series were again carried out for the measurements with 0 dBm transmission power and five others for the measurements with 4dBm transmission power. On the other hand, the long-range mode was used to transmit the data with 125 kbps LE coded. Two series of measurements, each with 0dBm and 8 dBm as transmission power, were used to transmit the data from one transceiver to the other.
The Bluetooth 5 configuration parameters and measurement results in high-speed mode with 0 dBm transmit power are summarized in Table 12.

Table 12: High Speed Modus with 0 dBm

transmission power	**Data amount**	**ATT_MTU**	**Conn_interval**	**DLE**	**PHY**	**Max distance**	**throughput**	**power consumption**	**Time to transfer**
O dBm	1024 Bytes	23	7.5 ms	off	2M	51 m	30,19 kbps	8,6 mA	277.8 s
		158	50 ms	on	2M	44 m	207,4 kbps	9,6 mA	40,4 s
		247	50 ms	on	2M	51 m	28,5 kbps	3,5 mA	296,9 s
		247	50 ms	off	2M	44 m	41,2 kbps	8,6 mA	203,4 s
		247	400 ms	on	2M	44 m	44,8 kbps	8,3 mA	187,1 s

Table 12 shows that the maximum range is 51 meters. This range was achieved in the first and third scenarios. While 30.19 kbps, 8.6 mA and 277.8 s were measured to reach this range in the first series of measurements, these are 28.5 kbps, 3.5 mA and 296.9 s in the third series of measurements. In the second, fourth and fifth series of measurements only a maximum of 44 meters could be achieved.

The maximum throughput is 207.4 kbps and was measured in the second series of measurements. Lowest power consumption was measured in the third series of measurements. With 4dBm a maximum range of 53 meters was reached. The lowest power consumption was measured in the third series of measurements.

With 4dBm a maximum range of 53 meters was reached. This range could only be achieved in the first series of measurements. The transmission time for the entire data set was 856.4 seconds. The maximum throughput was measured at 108.3kbps with a range of 22 meters. In the fourth series of measurements, a connection could be established at 53 meters. However, this broke off during data transmission. Table 13 summarizes the configuration parameters and measurement results of the Bluetooth 5 measurement series in high-speed mode and 4dBm transmission power.

In long-range mode, with a transmission rate of 125kbps, a maximum range of 28 meters was achieved with 0dBm. To achieve this range, a maximum ATT packet size of 247 bytes, 50ms configured as the connection interval, and DLE enabled. A throughput of 15kbps, a power consumption of 12.7mA and 363.37s to transfer the total amount of data was determined. Increasing the transmit power to 8 dBm reached 60 meters and measured a maximum throughput of 12.2 kbps. A total of 687.12 seconds were needed to transfer the data.

Table 13: High Speed Modus with 4 dBm

transmission power	Data amount	ATT_MTU	Conn_interval	DLE	PHY	Max distance	throughput	power consumption	Time to transfer
4 dBm	1024 Bytes	23	7.5 ms	off	2M	53 m	9,8 kbps	4,7 mA	856,4 s
		158	50 ms	on	2M	51 m	74,3 kbps	9,4 mA	112,9 s
		247	50 ms	on	2M	51 m	79,3 kbps	10,3 mA	105,7s
		247	50 ms	off	2M	51 m	24,3 kbps	9 mA	345 s
		247	400 ms	on	2M	22 m	108,3 kbps	12,8 mA	77,5 s

4.2.2 Outdoor measurements

The measurements were repeated in the open field near the village of Ispringen. First, measurements were made using Bluetooth 4.2 using various configuration parameters. As with the indoor experiment, the data was transmitted at 0 and 4dBm. For this, the maximum (247 bytes) and the minimum (23 bytes) configurable ATT_MTU packet size have been configured. The same parameters were chosen for the trial with Bluetooth 5 in high-speed mode. In long-range mode, the maximum configurable transmission power, 8dBm, was used again. Figure 4 gives an overview of the measurement condition in the free field. The Development Kit, which is connected to the computer, has been configured as a sender. On the horizon, marked by the red arrow, the receiver was placed. This item defines the maximum range of the uninterruptible connection with the transmitter.

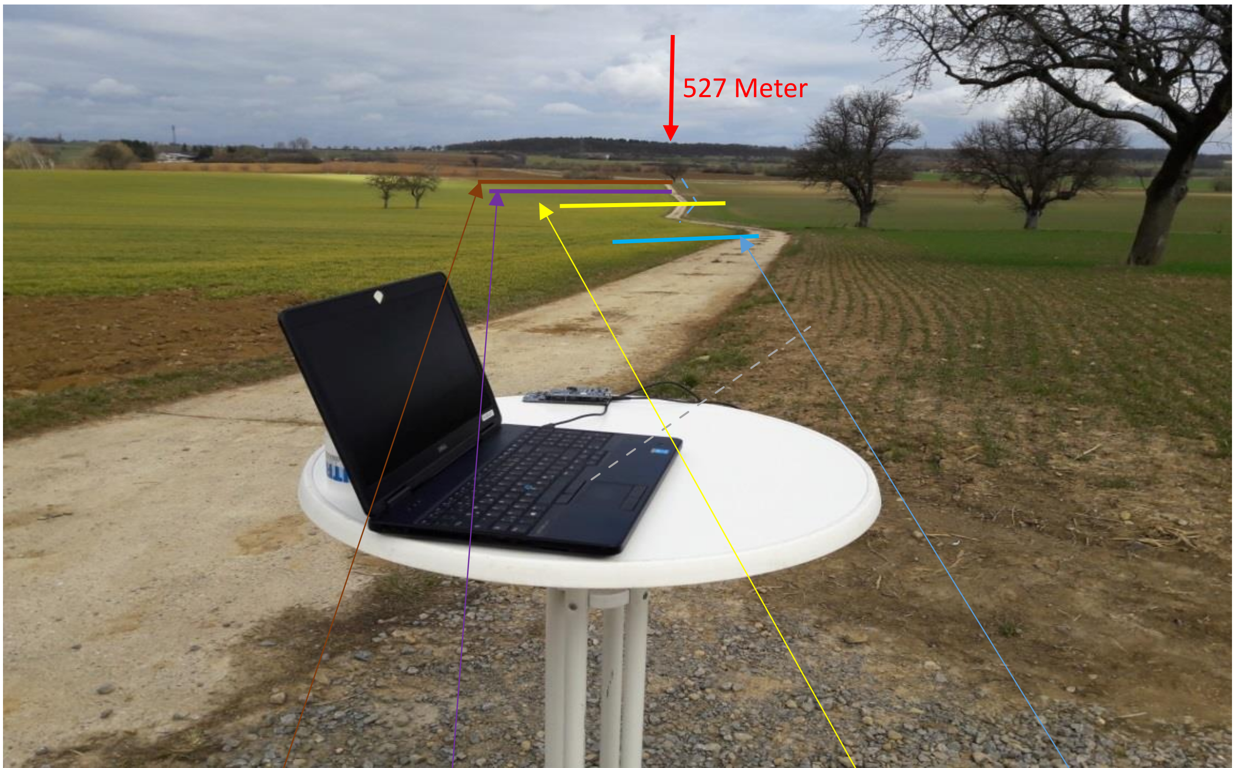


Figure 7: Summary of the measurement results in the open field

- Measurements with Bluetooth 4.2 in free field

Table 14 presents the measurement results of the first measurement series outdoors with 0dBm. With a connection interval of 7.5ms, an ATT_MTU of 23 bytes and with DLE disabled, a maximum range of 405 meters was reached with the highest throughput. With the maximum connection interval and ATT_MTU set to 247, the maximum range could not be achieved. The maximum throughput was still measured on the last measurement series, with the maximum connection interval and the maximum ATT_MTU packet size configured. The maximum throughput is 74.6 kbps.

Table 14: Outdoor measurements with Bluetooth 4.2 and 0dBm

transmission power	Data amount	ATT_MTU	Conn_interval	DLE	PHY	Max distance	throughput	power consumption	Time to transfer
0 dBm	1024 Bytes	23	7.5 ms	off	1M	405 Meter	14,5 kbps	5,2 mA	577,1 s
		247	50 ms	on	1M	255 Meter	26,6 kbps	8,6 mA	316 s
		247	50 ms	off	1M	255 Meter	12,4 kbps	8,4 mA	203,4 s
		247	400 ms	on	1M	355 Meter	74,6 kbps	14,2 mA	112,5 s

Increasing the maximum transmit power has reached a maximum range of 455 meters with a throughput of 283.5kbps. For this purpose, 50 ms were configured as the connection interval and a maximum ATT packet size of 247 bytes. In the fourth series of measurements, a maximum range of 55 meters was achieved. However, a very high throughput (790kbps) was achieved (see Table 15).

Table 15: Outdoor measurements with Bluetooth 4.2 and 4dBm

transmission power	Data amount	ATT_MTU	Conn_interval	DLE	PHY	Max distance	throughput	power consumption	Time to transfer
4 dBm	1024 Bytes	23	7.5ms	off	1M	455 Meter	55,5 kbps	7 mA	151,2 s
		247	50ms	on	1M	455 Meter	283,5 Kbps	12,7 mA	30 s
		247	50 ms	off	1M	455 Meter	54,2 Kbps	10,5 mA	154,7 s
		247	400 ms	on	1M	55 Meter	790 kbps	14,4 mA	10,6 s

- Measurements with Bluetooth 5 in the free field

Table 16 shows the measurement results in the high-speed mode (data transmission LE 2M) in the free field. 65 meters were reached at all configuration parameters maximum. The highest throughput was achieved with 247 ATT_MTU and a connection interval of 400ms.

Table 16: High speed mode with 0dBm outdoors

transmission power	Data amount	ATT_MTU	Conn_interval	DLE	PHY	Max distance	throughput	power consumption	Time to transfer
0 dBm	1024 Bytes	23	7.5ms	off	2M	65 Meter	235,1 kbps	12,02 mA	35,6 s
		247	50ms	on	2M	65Meter	1227 kbps	14,5 mA	7 s
		247	50 ms	off	2M	65 Meter	361,1 kbps	12,63 mA	23,2 s
		247	400 ms	on	2M	65 Meter	1283 kbps	15,13 mA	6,5 s

If the transmission power is increased by 4dBm, a maximum distance of 355 meters is reached. This range was achieved with a throughput of 182kbps and corresponds to the maximum distance for a stable connection. At 400 meters, the connection was still possible, but the total amount of data could not be transmitted due to disconnections (see Table 17).

Table 17: High speed mode with 4dBm outdoors

transmission power	Data amount	ATT_MTU	Conn_interval	DLE	PHY	Max distance	throughput	power consumption	Time to transfer
4 dBm	1024 Bytes	23	7.5ms	off	2M	355 Meter	41,6 kbps	10,7 mA	201,7 s
		247	50ms	on	2M	355Meter	182 kbps	12,5 mA	46,9 s
		247	50 ms	off	2M	355 Meter	26 kbps	5,2 mA	322,3 s
		247	400 ms	on	2M	65 Meter	983,4 kbps	19,2 mA	8,5 s

In long-range mode, a maximum range of 527 meters at 8dBm has been achieved. This is the point to which a stable connection was possible. At 550 meters, a connection was still possible, but the entire amount of data could not be transferred. An ATT_MTU of 247 and a connection interval of 50ms were set. It achieved a throughput of 18.01 kbps and a power consumption of 13.23mA. The transmission time for the entire data set was 465, 52 seconds. In the city center of Pforzheim, a maximum range of 230 meters was achieved with the same parameters. For this a throughput of 125kbps was measured. Figure 5 shows the measurement condition for measurements in the city center.

Figure 8: the maximum range in a city center

By contrast, only 95 meters could be reached when measuring in the forest. At 110 meters, a connection was still established, but only a third of the total data could be transferred before the connection was lost. This is 35 meters more than the maximum indoors range. Figure 8 gives an overview of the conditions in the forest.

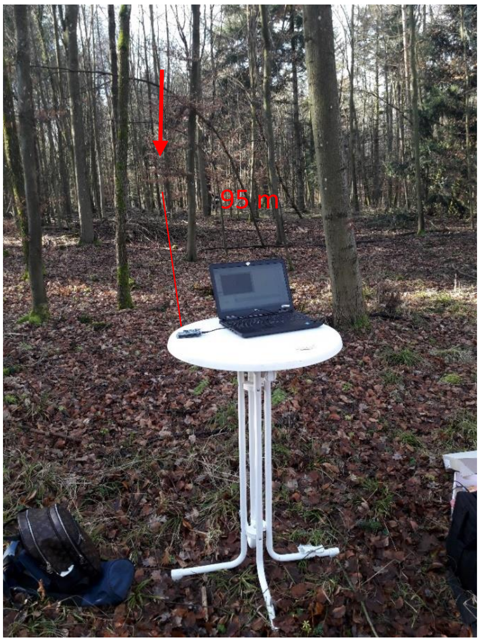


Figure 9: the maximum range in the forest

5 Evaluation of the measurement results

Based on the indoor and outdoor results presented, the communication range of Bluetooth Low Energy versions 4 and 5 can be compared. Furthermore, the energy consumption can be calculated and a statement about the effect of the setting of different configuration parameters on a Bluetooth low-energy connection can be made. Table 18 summarizes the measurement results of the indoor and outdoor experiments.

Table 18: Summary of measurement results indoors and outdoors

BLE Version	Legend	distance	transmission power	throughput	power consumption	Time to transfer	ATT_MTU	Conn-interval	DLE	PHY
	Measurements indoors									
4		51 m	0dBm	80,7 kbps	8,02 mA	104 s	158 Bytes	50 ms	ON	1M
4		56 m	4dBm	101 kbps	10,6 mA	83,9 s	247 Bytes	50 ms	ON	1M
5		51 m	0dBm	28,5 kbps	3,5 mA	296,9 s	247 Bytes	50 ms	ON	2M
5		51 m	4dBm	79,3 kbps	10,3 mA	105,7 s	247 Bytes	50 ms	ON	2M
5		28 m	0dBm	14,95 kbps	12,7 mA	561,15 s	247 Bytes	50 ms	ON	Coded 125 kbps
5		60 m	8dBm	12,2kbps	10,4 mA	687,12 s	247 Bytes	50 ms	ON	Coded 125 kbps
	Outdoor measurements									
4		405 m	0dBm	14,5 kbps	5,2 mA	577,1 s	23 Bytes	7,5 ms	OFF	1M
4		455 m	4dBm	283,5 kbps	12,7 mA	30 s	247 Bytes	50 ms	ON	1M
5		65 m	0dBm	1283 kbps	15,13 mA	6,5 s	247 Bytes	40 ms	ON	2M
5		355 m	4dBm	182,2 kbps	12,5 mA	46,9 s	247 Bytes	50 ms	ON	2M
5		527 m	8dBm	18,01 kbps	13,23 mA	465,52 s	247 Bytes	50 ms	ON	Coded 125 kbps

BLE 5: Bluetooth Low Energy Version 5

BLE 4: Bluetooth Low Energy Version 4

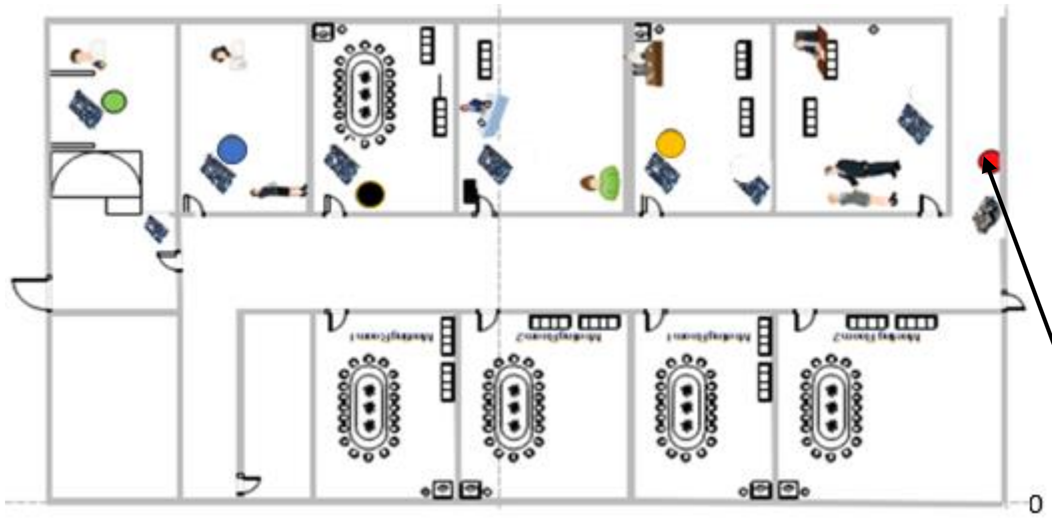


Figure 10: Summary of Indoor Measurements (See also Table 18)

Transmitter with transmission power: 0dBm, 4dBm und 8 dBm

PHY: LE 1M, LE 2M und LE coded 125 kbps

ATT-MTU: 23 Bytes,158 Bytes und 247 Bytes

Figure 11: Summary of the measurement results in the open field

Transmitter with transmission power: 0dBm, 4dBm und 9 dBm

PHY: LE 1M, LE 2M und LE coded 125 kbps

ATT-MTU: 23 Bytes,158 Bytes und 247 Bytes

From the 10 series of measurements presented in section 4.2.1, it can be seen that the length of the data packets and the connection interval play a major role in the transmission speed and stability of a Bluetooth connection.

In the first measurement series of the first scenario, in normal mode, it can be seen that only a small throughput can be achieved with the smallest configurable connection interval and deactivated DLE. When configuring small connection intervals, fewer data packets are transmitted within one connection interval. As a result, more time is needed for data transfer and throughput is reduced. Disabling the DLE feature sets the maximum packet length to 27If you still configure a longer ATT package; the packages are divided into small packages. Each package contains an overhead that must be taken into account for each package. In addition to overhead, IFS (Interframe Space) must also be considered. For this reason, a comparison is made to the third series of measurements in which DLE is activated. It turns out that significantly more time is required to transmit the same amount of data in the fourth series of measurements. It can be seen from Tables 15 and 16 that the maximum allowable data packet size and the connection interval have been pre-configured. This results in a very high throughput and only a short range. The reasons for this are: When transmitting large packets in large connection intervals, many payloads are transmitted in one interval. If a data packet is lost at the beginning of the transmission, the entire interval must be waited for to resend the packet. This waiting time leads to a reduction of the throughput over the distance and to an unstable connection.

From Table 18, it can be seen that Bluetooth 5 can improve range both indoors and out. Inside, a maximum range of 60 meters was achieved with the coded PHY and a transmission power of 9 dBm. In normal mode, the maximum range is 56 meters. This can be an improvement of about 9% can be found. For outdoor measurements, a maximum of 527 meters was achieved in long-range mode and a maximum of 455 meters in normal mode. Bluetooth 5 brings with it an improvement of about 15%. It can be concluded that Bluetooth 5 does not quadruple the range mentioned in Chapter 2. However, it should be noted that in the indoor scenario, the materials of construction have a very large impact on how the signal propagates. To obtain more accurate percentages, more series of measurements must be performed in different environments.

Figure 12 shows the power consumption over the distance to reach the maximum indoor range. This was calculated using the formula $P = UI$, where P is the power [mW], U [V] is the voltage (3V) and I is the measured current [mA].

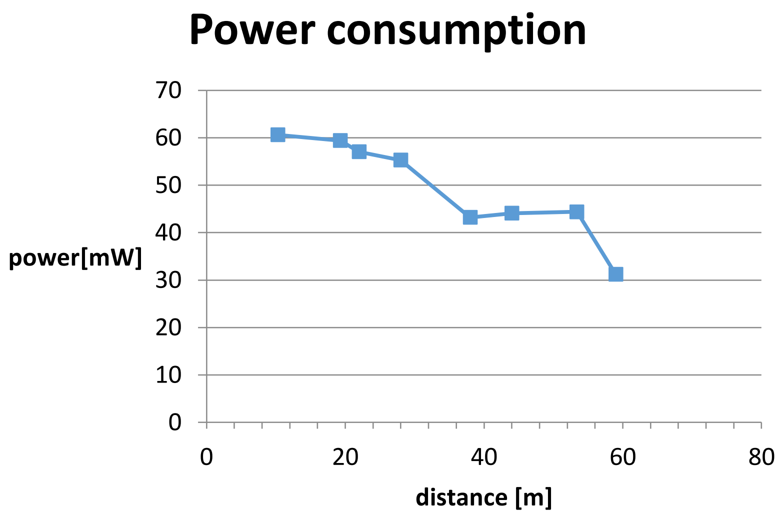


Figure 12: Power consumption over the distance

From the diagram (Figure 12), it can be concluded that the power of the transmitter continuously decreases with distance. This is due to the power-saving mode of Bluetooth Low Energy. With the distance, the packets are lost over the radio link. Power consumption is minimized until the next interval for the new transmission of the lost packet (standby). Power consumption is minimized until the next interval for the new transmission of the lost packet (standby). The reduction in power thus compensates for the longer transmission time and leads to a reasonably constant energy consumption. Figure 13 shows the energy consumption versus distance for the maximum range with encoded indoor PHY. At this point, it should be noted that the time for the transmission of 1 megabyte was measured. At this point, it should be noted that the time for the transmission of 1 megabyte was measured. This point is exactly on the wall where people and furniture were placed.In addition to the floor reflection walls and objects reflect the Bluetooth signal very strong.

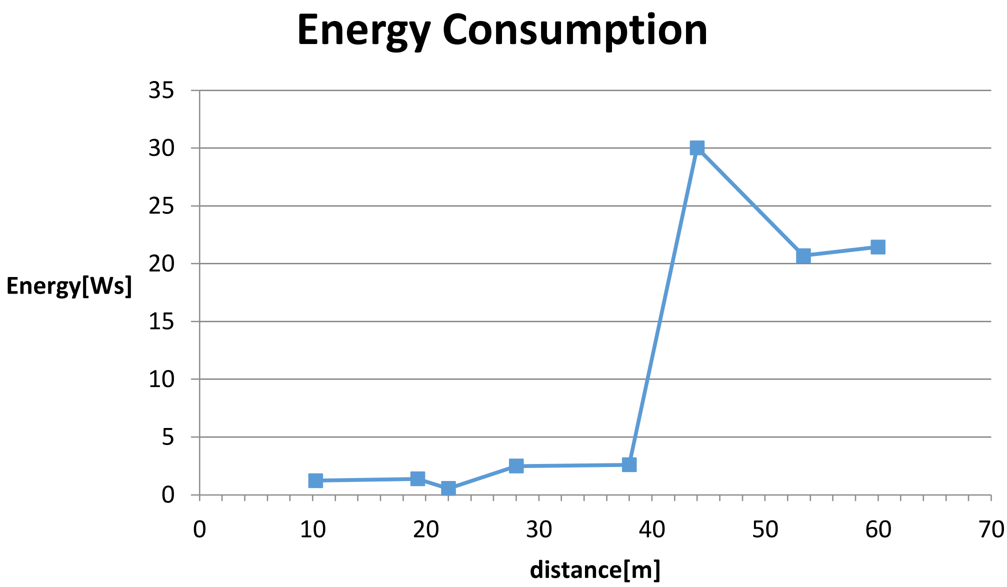


Figure 13: Energy curve for the maximum range indoors

A maximum range of 527 meters was reached in the open field. Compared to the indoor range, this is about nine times as high. Here, the Fresnel zone is free of obstacles. The weather conditions, the ground reflection and positioning of the transmitting antenna, however, have a negative effect on the radio signal. Figure 10 shows that a bend can be seen between 65 and 355 meters. Within this zone, no connection could be established in normal and high-speed mode. In 8dBm long-range mode, the data was received at low throughput, and more time was required to transfer the entire amount of data.

Figure 14 shows the power consumption over distance to reach the maximum range in the open field.

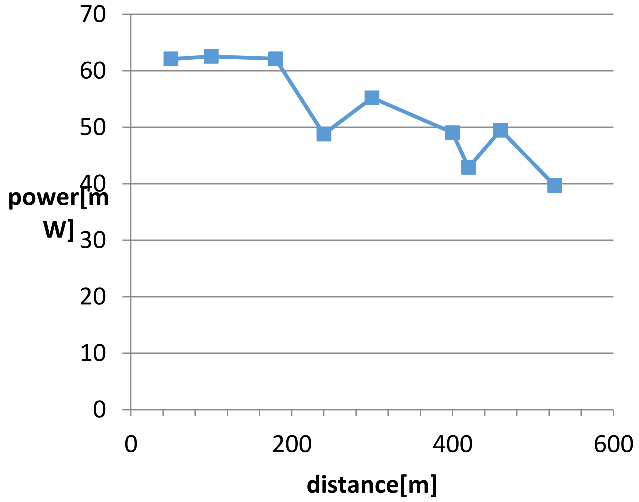


Figure 14: Power consumption for maximum outdoor range

Figure 15 shows the energy curve over the distance to reach the maximum range in the open field. Up to 200 meters, the power is still high enough to transmit the data with low energy. At 240 meters, the transmitter's performance drops due to increased ground reflection and diffraction. This results in high energy consumption. After diffraction, at 300 meters, the energy consumption first decreases and then increases continuously with the distance.

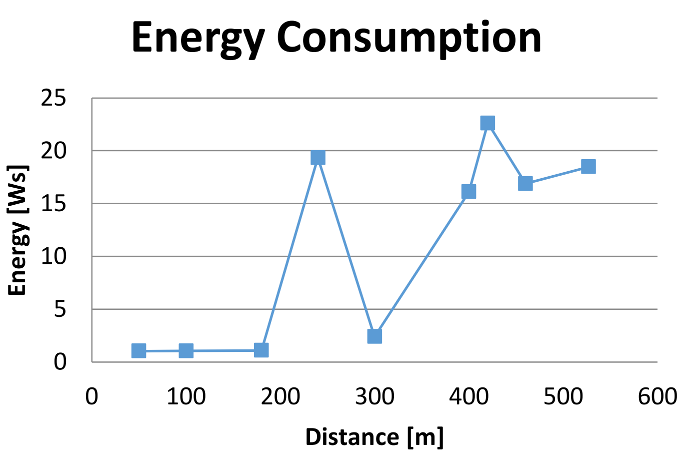


Figure 15: Energy consumption for maximum outdoor range

6 Summary

The aim of this white paper was to experimentally determine the communication range, data throughput and power consumption of Bluetooth. At the beginning, a Bluetooth low-energy connection was set up between two Preview Development Kits of the nRF52840 from Nordic Semiconductor. Subsequently, the measurements were carried out indoors and outdoors. The results show that Bluetooth 5 with encoded PHY (125 kbps) improves the communication throughput with low throughput. However, these improvements do not confirm the promised 4-way range of the Bluetooth specificationIn addition to the floor reflection and environmental conditions, the walls and the furniture, depending on the material, very much reflect the Bluetooth radio signal. Added to this is the limitation of the softdevice used. Advertising was done with PHY 1M. This theoretically results in the same range for all transmission modes. The high-speed and the long-range mode works in this case only for an existing connection. After many improvements, Nordic released an experiment on May 31, 2018 that proves the full support of the long-range feature (7).

This experiment can be found at the following link and complements this white paper:

https://blog.nordicsemi.com/getconnected/tested-by-nordic-bluetooth-long-range?utm_campaign=Blog%20update%20notifications&utm_source=hs_email&utm_medium=email&utm_content=63381729&_hsenc=p2ANqtz--cLep3gV0YdAQqfqaRirkI6CmHvii9jiRshV5waWfjrauS-uCFnL-zyDPQptywfYoqGkLgVUGQiYQKFqJW5zsC7VktF1f-J9fJs4BX2wTYivg8f28&_hsmi=63381729

A maximum range of 527 meters has been achieved outdoors. This is quite sufficient to use the low power sensors, such as moisture sensor in agriculture, to monitor the plants at a maximum distance of 527 meters. Thus, the sensor values can also be read with a smartphone, tablet or laptop from a great distance and, for example, forwarded to a cloud for processing.

Inside, the maximum range was 60 meters. This allows many practical applications to be realized. In the medical field, for example, Bluetooth 5 with coded PHY can be used in combination with low-power sensors to monitor patients' health within 60 meters and to check if a patient leaves the hospital unauthorized. Figure 16 shows a concept for the use of Bluetooth 5 in the medical field.

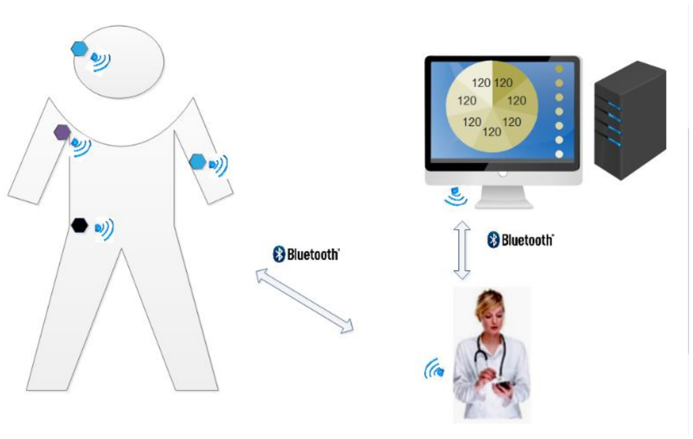


Figure 16: Example concept for the use of Bluetooth 5 in the medical field

In addition, Bluetooth 5 can be used, for example, in the industry to control machines within 60 meters. Figure 17 shows a concept for Bluetooth 5 in the industry, where by the temperature of the operated machines can be read out with the sensors and stored and analyzed via Bluetooth Low Energy in a server. However, long-range mode is not suitable for faster processing because the data is encoded with eight symbols and requires more time to transmit than normal and high-speed modes.

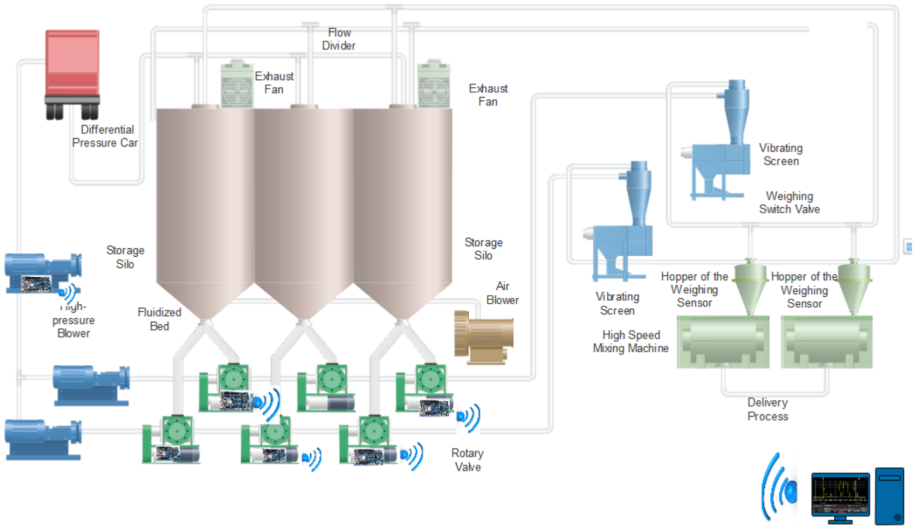


Figure 17: Concept for the use of Bluetooth 5 in the industrial sector

In high-speed mode, a throughput of 1283 kbps was measured. This can be used in the automotive industry audio transmission or video transmission of the rear view camera. Furthermore, the high-speed mode can be used in the household with a digital peephole. For example, a camera module could be connected via the I2C or SPI interface, and the recorded video frame could be transmitted via Bluetooth Low Energy to a smartphone that supports Bluetooth 5.

As a next experiment it would be interesting to explore the possibilities of IPv6 transmission via Bluetooth 5 in different transmission modes.

7 List of Nordic products related to this Whitepaper

nRF52-DK // RFMCU1061
buy online: https://www.rutronik24.com/product/nordic/nrf52-dk/7544091.html

The nRF52 DK is a versatile single board development kit for *Bluetooth*® low energy, ANT and 2.4GHz proprietary applications using the nRF52832 SoC. This kit supports development for the nRF52832 and nRF52810 SoC. The kit is hardware compatible with the Arduino Uno Revision 3 standard, making it possible to use 3rd-party shields that are compatible to this standard. An NFC antenna can be connected the kit to enable NFC tag functionality. The kit gives access to all I/O and interfaces via connectors and has 4 LEDs and 4 buttons which are user-programmable.It supports the standard Nordic Software Development Tool-chain using Keil, IAR and GCC. Program/Debug options on the kit is Segger J-Link OB.

nRF52832- QFAA Samples // RFMCU1220
buy online: https://www.rutronik24.com/product/nordic/nrf52832-qfaa-t-bxo/8515166.html

The nRF52832 SoC is a powerful, highly flexible ultra-low power multiprotocol SoC ideally suited for *Bluetooth*® Low Energy, ANT and 2.4GHz ultra low-power wireless applications. The nRF52832 SoC is built around a 32-bit ARM® Cortex™-M4F CPU with 512kB + 64kB RAM. The embedded 2.4GHz transceiver supports Bluetooth Low Energy, ANT and proprietary 2.4 GHz protocol stack. It is on air compatible with the nRF51 Series, nRF24L and nRF24AP Series products from Nordic Semiconductor.

The nRF52832 has hardware support on-chip for Bluetooth 5. This includes high throughput and advertising extension.

Power Profiler Kit nRF6707 // RFMCU1149
buy online: https://www.rutronik24.com/product/nordic/nrf6707/8220111.html

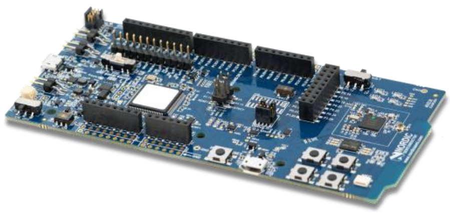
The Power Profiler Kit is an easy to use tool for the measurement and power consumption optimization of embedded solutions.

The Power Profiler Kit plugs directly into the nRF51 DK and nRF52 DK development kits through the Arduino Uno Revision 3 standard pin headers, in combination with the special power measurement header on these kits. This allows easy power profiling with a minimum of hardware work needed. There’s also an additional connector for power consumption measurements on external boards, so you can connect and power profile your final hardware as well. It supports Vcc levels between 1.8V and 3.3V and has an onboard regulator that will supply up to 70mA to external applications.

nRF52840-DK // RFMCU1331
buy online: https://www.rutronik24.com/product/nordic/nrf52840-dk/10422794.html

The nRF52840 DK is a versatile single board development kit that supports development using the following protocols:

- Bluetooth 5
- Bluetooth Low Energy
- Bluetooth mesh
- Thread
- 802.15.4
- ANT
- 2.4GHz proprietary



The kit is hardware compatible with the Arduino Uno Revision 3 standard, making it possible to use 3rd-party shields that are compatible to this standard. An NFC antenna can be connected the kit to enable NFC tag functionality. The kit gives access to all I/O and interfaces via connectors and has 4 LEDs and 4 buttons which are user-programmable.
It supports the standard Nordic Software Development Tool-chain using Segger Embedded Studio, Keil, IAR and GCC. Program/Debug options on the kit is Segger J-Link OB.

nRF52840-Dongle // RFMCU1350
buy online: https://www.rutronik24.com/product/nordic/nrf52840-dongle/10720468.html

The nRF52840 Dongle is a small, low-cost USB dongle for Bluetooth® low energy, Bluetooth mesh, Thread, ZigBee, 802.15.4, ANT and 2.4GHz proprietary applications using the nRF52840 SoC. The Dongle is the perfect target hardware for use with nRF Connect for Desktop as it is low-cost but still support all the short range wireless standards used with Nordic devices. The dongle has been designed to be used as a wireless HW device together with nRF Connect for Desktop. For other use cases please do note that there is no debug support on the Dongle, only support for programming the device and communicating through USB.

It is supported by most of the nRF Connect for Desktop apps and will automatically be programmed if needed. In addition custom applications can be made and downloaded to the Dongle. It has a user programable RGB LED, a green LED, a user programmable button as well as 15 GPIO accessible from castellated solder points along the edge. Example applications are available in the nRF5 SDK under the board name PCA10059. The nRF52840 Dongle is supported by nRF Connect for Desktop as well as programming through nRFUtil.

nRF52840-QIAA Samples // RFMCU1166
buy online: https://www.rutronik24.com/product/nordic/nrf52840-qiaa-r/8274101.html

The nRF52840 has full hardware and software support for all the new features introduced in Bluetooth 5. The SoC is designed around an ARM Cortex-M4 CPU with floating Point unit (FPU) and has 1MB flash with cache and 256kB RAM. As such it has the ability to support complex and demanding applications as a single chip solution. It offers a wealth of peripherals that include NFC, USB and multiple interface options including Quad SPI (QSPI). Security is paramount in today's IoT designs and the nRF52840 has high-end security features included to achieve best in clas security with an ARM CryptoCEll cryptographic system on chip and a full AES 128-bit encryption suite.

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