# 2

# Low Power Wireless Communications

## 2.1 Introduction

Reducing the power consumption of radios has been a topic of research for quite a long time. In recent years, the search for energy efficient means of communication and constant effort to lower the power consumption of wireless transceivers have been primarily driven by the growing popularity of the internet of things [1]. Still today, the consumption of radios is one of the primary obstacles to making the IoT concept a reality. Since the available energy sources have a very limited capacity, especially in size-critical applications, reducing the power consumption of sensor nodes remains the only mean of increasing their autonomy.

A wide range of wireless technologies exist that provide a different set of capabilities tailored for different applications. Wireless devices typically trade power consumption, data rate and sensitivity (which can be directly translated to range), although there are other important quantities, such as dynamic range and interference rejection, and finally size and cost, that play an important role. Some of the well-known wireless technologies are presented in Figure 2.1, that gives a qualitative comparison of consumption and range. Typically, larger range requires larger power consumption. However, a third axis would be needed to show a more complete picture. This third axis would be the data rate (or alternatively bandwidth). LoRa, SigFox and NB IoT devices manage to extend the range without an increase in power consumption at the cost of data rate, which further means that only a limited amount of information can be transmitted within a given time. These technologies were intended for use in wide area networks, to gather data from sensors that only need to transmit several bits every few hours (e.g. temperature sensors). Data rates that can be found in these radios typically vary from only 10 b/s up to 50 kb/s, which is why they are also referred to as the ultra narrowband (UNB) radios.

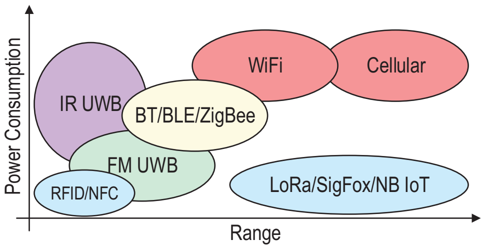



**Figure 2.1** Power consumption and range of different wireless technologies.

Radio Frequency Identification (RFID) and Near Field Communication (NFC) provide the lowest power consumption. This is mainly owing to the low communication range, that is sometimes only a few centimeters, and the asymmetric link, where the burden is placed on the reader, allowing to simplify the tag. The RFID/NFC tags can consume zero power, meaning that they can be entirely powered by the reader, but their capabilities are also limited to sending only a few bytes of information, such as the ID of the tag. An RFID tag can be made very small and is often dominated by the antenna size (especially in the sub-GHz bands), whereas a reader is quite large and consumes a lot of power as it may need to transmit at watt levels.

A similar kind of asymmetry can be found in cellular networks. In this case most of the burden is placed on the base station that has access to the power grid, making its size and consumption a less important issue. This allows to reduce the size and complexity of the battery-powered, hand-held devices, while still maintaining a link over several kilometers and providing data rates on the order of 100 Mb/s. The principle is similar to the WiFi, with the burden mainly placed on the fixed device, allowing higher autonomy for the mobile devices. The difference compared to the cellular technologies is the range.

Unlike the previously mentioned standards, Bluetooth (and it's derivation Bluetooth Low Energy or BLE) and ZigBee provide a fully symmetrical link, meaning that the same transceiver is used on both sides. These radios are commonly used to provide low power wireless connectivity between two or more battery powered devices. In particular, Bluetooth has become the most widely used standard for low power connectivity in consumer applications. It provides complete wireless connectivity services, not just wireless transport, and is commonly implemented in audio streaming, data transfer and broadcasting devices. Although initially designed for small networks, consisting of up to seven peripherals connected to a master device (such as a computer, or a smart phone), Bluetooth has evolved over the years and now supports different network topologies with a much larger number of devices. It targets ranges from tens to hundreds of meters, and data rate in the order of 1 Mb/s. The fact that Bluetooth is already a dominant technology in the consumers' market means that most manufacturers want to use it in their devices regardless of whether it is really optimal for a specific application. This greatly reduces the effort and time to market that would otherwise be necessary with a custom made radio.

ZigBee, or the IEEE 802.15.4, is a similar standard with the same communication distance and lower data rates that go up to 250 kb/s. Unlike Bluetoth, it targets mainly industrial applications, and therefore the emphasis is on security, robustness and scalability, providing support for high node counts. As of 2012, enhanced ZigBee specifications also include secured connectivity to batteryless devices, powered from energy sources like motion, light or vibration.

An interesting candidate for low power communications are ultra-wideband (UWB) devices. The particularity of these devices is that the data rate is not directly linked to the bandwidth of the transmitted signals. When talking about UWB the occupied spectrum is typically much larger than required by the communication speed. Although it seems like they are wasting a very precious resource, they provide capabilities that cannot be easily achieved with classical narrowband radios. Large bandwidth relaxes constraints on the precision of the frequency synthesizer. This allows the implementation of radios without Phase Locked Lops (PLL) resulting in higher agility and making them more suitable for duty cycling. The same property also eliminates the need for a precise frequency reference, such as a quartz oscillator, allowing the reduction in size and cost of the product. UWB signals are more difficult to detect and jam, and due to their low Power Spectral Density (PSD) do not interfere with neighboring narrowband signals. Furthermore, they are capable of resisting strong interferers and operating in multi-path environments without a severe loss in performance.

In principle, the UWB radios that are in the focus of this book (targeting low to medium data rates and low power) fit between the BLE and RFID devices. They are not able to achieve the same sensitivity at the same data rate as the BLE, but they can provide a lower power consumption, size and cost. At the same time, there are no fully passive UWB solutions that can compete in the RFID space, but they provide a symmetric link, longer range and better overall performance.

Before going into the in depth analysis of the FM-UWB, this chapter will summarize and compare the key radios targeting a similar application space as the FM-UWB. The emphasis is on low power techniques, targeting low to medium data rates and a fully symmetric link. Since the network performance is almost entirely determined by the receiver performance, the rest of the chapter will be devoted to them.

## 2.2 Narrowband Communications

Many different narrowband techniques have been developed targeting different WSN or IoT scenarios. Today, the absolute leader in the consumers' market is the Bluetooth, which can be found in almost every portable device. ZigBee found its market in industrial automation and puts more emphasis on robustness and security. Both of these standards target distances up to 100 m at moderate data rates.

Several recently emerged standards, such as SigFox, LoRa and NB IoT are developed to cover lower data rates and provide a range of several kilometers. This is typically done by reducing the data rate. Since the probability of error depends on energy per bit $E_b$, that is a product of signal power and symbol duration, communication range can easily be extended by using longer symbol duration. Symbol duration is inversely proportional to the signal bandwidth, meaning that very long symbols occupy a very narrow frequency band, hence the name ultra narrowband. The commercial UNB receivers consume a similar amount of power as BLE transceivers [2] but, owing to lower data rates, achieve sensitivity better than $-140$ dBm (compared to BLE receivers that fall in the range between $-80$ dBm and $-100$ dBm). Combined with the output power specified above 10 dBm, LoRa radios typically provide a link budget above 150 dB.

An interesting class of receivers are the wake-up (WU) receivers. These have mainly been a topic of academic work, and haven't yet been truly adopted by the industry. Unlike the previously mentioned receivers, the WU receivers generally do not comply with any of the existing standards, therefore allowing much more freedom in optimizing different system parameters. The idea behind wake-up receivers is to constantly listen to the channel and check whether there is a signal being transmitted. Once they detect the presence of a correct sequence, they turn on the main receiver that will be used for data reception. Clearly, for the concept to work, the wake-up receivers must consume a very small amount of power. This usually comes at a price in sensitivity and speed, which is an acceptable trade-off in this case. Since WU and BLE receivers have have gained a lot of traction in recent years they will be the subject of study throughout this section.

### 2.2.1 Bluetooth Low Energy

Aside from dominating the market, Bluetooth and BLE transceivers are often a topic of academic work exploring new potential architectures and looking into different trade-offs between power consumption and performance. BLE is typically targeting a data rate of 1 Mb/s, although most commercial devices support higher data rates. It is intended as a standard that provides a low power connection between portable devices and sensor nodes.

The BLE uses the ISM band located between 2.4 GHz and 2.48 GHz. The used band is split into 40 channels, each 2 MHz wide. The data is transmitted at 1 Mb/s using the Gaussian Frequency Shift Keying (GFSK), meaning that a Gaussian filter is used for pulse shaping. A 2 Mb/s option is added in the Bluetooth 5 specification. An optional Enhanced Data Rate (EDR) mode provides higher data-rates by using DQPSK and 8DPSK modulations. Output power is limited to 100 mW, or 20 dBm, this limit was increased from 10 dBm in the BT 5 specification in order to extend the maximum range to above 100 m. Minimum sensitivity of BLE devices is set to $-70$ dBm, although most devices are providing at least $-80$ dBm. Frequency hopping is used to avoid collisions with other BLE transceivers or unwanted interferers.

The relatively loose BLE requirements allow a simple transmitter architecture that can be optimized for low power consumption. A typical BLE transmitter block diagram is shown in Figure 2.2. The transmitted RF signal is directly synthesized by a PLL. This approach allows to save power by avoiding mixers and quadrature signal upconversion. The modulated signal can be injected in different points of the PLL. Figure 2.2 shows the case where the VCO/DCO is directly driven by the modulated signal. A different

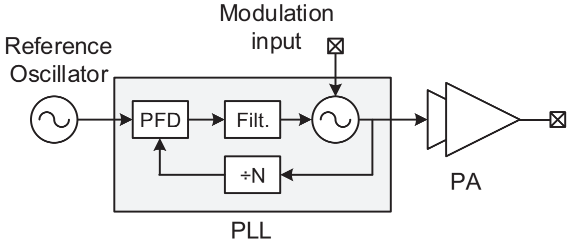
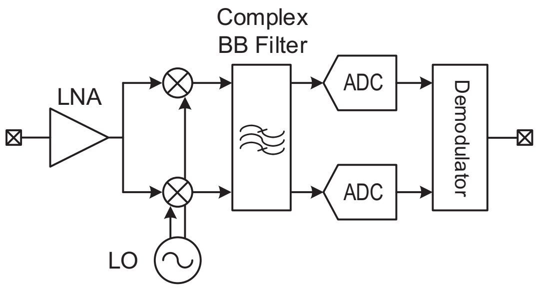


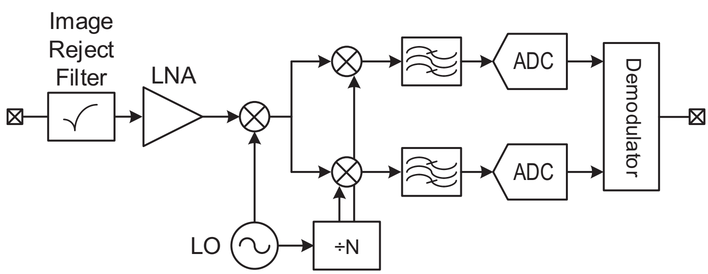

**Figure 2.2** Typical BLE transmitter block diagram.

approach would be to inject the signal at the fractional frequency divider (usually controlled by a sigma-delta modulator). Injecting a signal at this point provides a good frequency control, but the approach suffers from the limited PLL bandwidth. Increasing the loop bandwidth to accommodate the needed signal bandwidth increases phase noise of the PLL. For this reason a hybrid approach has been used in some implementations, and is referred to as the two point modulation [3]. In this case signal is partially injected directly to the VCO to compensate for the limited bandwidth of the PLL. One of the advantages of the GFSK modulation, used by BLE, is that it is a constant envelope modulation. This means that the signal amplitude remains unchanged during transmission, which allows for an efficient implementation of the power amplifier. In general, power amplifiers are highly dependent on the characteristics of the transmitted signal. Non-constant envelope signals, such as $\pi$/4-DQPSK, require linear power amplifiers which are always less efficient. The advantage of non-constant envelope signals is better spectral efficiency, meaning that they occupy a smaller frequency band and leak less into adjacent channels. Efficient spectrum utilization is an important issue in high-performance systems, while it is usually sacrificed in low-power systems in order to obtain better power efficiency.

The two most commonly used receiver architectures in BLE receivers are the sliding IF and the low IF architectures shown in Figure 2.3. The low IF receiver was derived from the zero IF (or direct conversion) receiver. As the name says, such a receiver converts the input RF signal directly to zero [4]. In order to prevent a loss of information, the receiver must perform a quadrature conversion, in other words it must separate the baseband signals by their phases. The advantages of the direct conversion receiver are the absence of image (interfering signal symmetrical to the useful signal with respect to the carrier frequency), simple architecture and use of low pass filters for channel selection. However, since the baseband signal is located around zero, these receivers suffer from increased flicker noise, LO leakage, dc offset and are sensitive to I/Q mismatch. Most of these drawbacks are resolved using the low IF receiver. Centering the baseband signal between 1 MHz and 2 MHz mitigates the problems with flicker noise and dc offset. An issue with a low IF receiver is that an image now appears at negative frequencies. This image must be suppressed by a sharp complex baseband filter (usually a polyphase filter) prior to digitizing the signal. When it comes to power consumption some authors claim that this type of receiver consumes a lot of power for frequency generation, as it needs to provide quadrature signals at the RF channel frequency [5, 6]. From this point of view the sliding IF receiver has




(a)




(b)

**Figure 2.3** Low power BLE receiver block diagrams, low IF (a) and sliding IF (b) receiver.

some interesting properties. Although the conversion is done in two steps, only one oscillator is used. The second LO is derived from the first using a fixed frequency divider. That mans that if the input frequency changes the IF changes as well, hence the name sliding IF. If the division ratio is even, quadrature signals are available practically for free. As frequency dividers are in any case needed for the PLL, second LO generation doesn't cause additional burden in terms of power. Since the first LO frequency is lower than the input signal frequency, the consumption of the VCO and the LO buffers is somewhat reduced. For example if the fixed division ration is 2 then the LO frequency should be $f_{LO} = 2/3 f_{in}$. Additional gain comes from the fact that the VCO doesn't need to generate a quadrature signal. As with all heterodyne receivers, the image might pose problems for the sliding IF receiver as well. This issue is commonly addressed by placing an external image reject filter that suppresses all signals at the image frequency.

**Table 2.1** Performance comparison of BLE receivers

| Ref. | Sens. [dBm] | Cons. [mW] | Eff. [nJ/b] | Data Rate [Mb/s] | Supply [V] | Mod. |
|---|---|---|---|---|---|---|
| Academic Work | | | | | | |
| [10] | −95 | 0.98 | 0.98 | 1 | 1 | GFSK |
| [11]* | −80 | 0.23 | 2.77 | 0.083 | 0.75 | FSK |
| [6] | −98 | 3.8 | 3.8 | 1 | 1.2 | GFSK |
| [5] | −90 | 5.5 | 5.5 | 1 | 0.6/1.2 | GFSK |
| [3] | −94.5 | 6.3 | 6.3 | 1 | 3 | GFSK |
| [12]* | −57.5 | 0.15 | 1.3 | 0.115 | 0.9/1.1 | OOK |
| Commercial Devices | | | | | | |
| TI CC2540 [13] | −93 | 39 | 19.5 | <2 | 2–3.6 | GFSK |
| PSoC 63 [7] | −95 | 22 | 11 | <2 | 1.7–3.6 | GFSK |
| nRF51822 [14] | −93 | 23 | 11.5 | <2 | 1.8–3.6 | GFSK |
| nRF52832 [15] | −96 | 16.2 | 8.1 | <2 | 1.7–3.6 | GFSK |
| EM 9301 [16] | −83 | 27 | 13.5 | <2 | 1.9–3.6 | GFSK |
| DA14580 [8] | −93 | 11.4 | 5.7 | <2 | 0.9–3.45 | GFSK |
| TC35679 [17] | −93.5 | 9.9 | 4.95 | <2 | 1.8–3.6 | GFSK |
| TC35681 [18] | −95.6 | 15.6 | 7.8 | <2 | 1.8–3.6 | GFSK |
| RSL 10 [9] | −94 | 9 | 4.5 | <2 | 1.1–3–3 | GFSK |

For all commercial devices reported sensitivity is at 1 Mb/s.
*BLE compatible WU receiver.

An overview of existing BLE receivers is given in Table 2.1. Key performance metrics are given for selected academic work, as well as for commercially available components. As seen in the table, most of commercial devices target sensitivity better than −90 dBm. The power consumption varies from 39 mW down to 9 mW in some of more recent implementations. It should also be noted that some of these implementations are parts of entire systems on chip (SoC), targeting IoT type of applications [7–9]. Most of them also come with an integrated DC-DC converter that converts the 3.3 V battery supply into voltages around 1 V, typically used by today's low power radios, and provide a low power sleep mode, making them suitable for duty cycling.

Seeing the consumption of devices reported in academic work it is clear that there is still room for improvement. Various techniques are found that enable different improvements. The receiver from [10] consumes less than 1 mW, while achieving sensitivity comparable to commercial devices. To achieve such low power the design relies heavily on current reuse. The input gain stages are stacked to maximize gain for a given bias current. Direct conversion receiver is used and the PLL provides an LO at twice the RF frequency. Such strategy is often seen in BLE radios as it reduces frequency pulling (frequency drift due to coupling to external signals) and provides an easy way to generate a quadrature LO. The design also demonstrates other useful tricks, such as placing the VCO circuitry inside the inductor to conserve area. This is possible because the magnetic field is mainly concentrated close to the conductor, and therefore the circuits in the middle have minimal effect on the inductor parameters. In this case the Q factor is degraded by 6%. In [3] a full BLE transceiver with an integrated DC-DC converter is presented. What makes this work interesting is that the LNA input and the PA output are sharing the same pad. All the passive components of the IO matching network are placed on chip, the only off-chip components required (aside from the crystal resonator) are the inductor and capacitor for the DC-DC converter. The matching network can be configured for transmit or receive mode using MOS switches. In the receive mode it also acts as a notch filter that attenuates the signal at the image frequency, hence eliminating the need for another external component.

The two receivers from [11] and [12] are not true BLE receivers in the sense that they do not conform to all the standard requirements, but they are BLE compatible receivers. This means that they can be used to decode information from a BLE compliant packet, but they are not as constrained as regular BLE receivers, allowing them to further reduce power consumption. They can be used to sample the RF channel instead of the main receiver and only wake up the main receiver when useful data is transmitted, thereby allowing global power reduction in the system. As seen in the table, they use lower data rates than those specified by the standard, allowing to reduce power while maintaining sensitivity. In order to allow for lower data rates, BLE packets on the transmitter side must be formed in a specific way (e.g. repeating the same bit several times), but such that they still conform to the standard. In work from [11], the input sequence is pre-coded such that after data whitening, that is mandatory in BLE, the output sequence gives a desired bit repetition to reduce the equivalent data rate. Following this, since the BLE packets have a limited payload length, there is a trade-off between data rate and the wake-up sequence length. The receiver from [11] uses a free running LC oscillator that is only calibrated once. Removing the PLL reduces power consumption, but also allows the receiver to start more quickly as there is no limit coming from the loop bandwidth. This approach allows to duty cycle the receiver at a bit level, further reducing the consumption, but also loosing approximately 3 dB in sensitivity. The problem with a free running LC oscillator is the precision, so the carrier offset must be tracked and corrected at IF. Given the small spacing between BLE channels the receiver could easily lock onto an undesired channel, which is the main downside of the receiver from [11]. The second BLE compatible receiver described in [12] uses quite a different approach. Instead of demodulating bits, it is detecting presence of the BLE signal on different advertising channels. The receiver is not capable of demodulating a GFSK signal, instead it is a simple envelope detector (ED) that detects the signal level at a selected BLE channel. In order to wake up the main receiver, a specific sequence of transmissions on different advertising channels must be sent. This approach allows for power reduction, owing to the demodulator simplicity, however the sensitivity is greatly degraded compared to similar receivers. Nevertheless, the work shows a very interesting way to exploit the available degrees of freedom, while providing compatibility with the BLE.

The Bluetooth standard has evolved significantly over the past two decades in order to adapt to the modern needs of a low power radio. At the same time, the hardware itself has undergone significant changes in a long lasting attempt to reduce size and power while improving performance. Still, while having a standard facilitates widespread use of BLE devices, it also imposes constraints and limits the achievable degrees of freedom. Once the constraints are gone, a large variety of different performances can be achieved. This is shown in the following section on wake-up receivers.

### 2.2.2 Wake-up Receivers

As the name suggests, the wake up receivers are used to listen to the communication channel and wake up the main receiver when data needs to be sent. The idea behind this is to reduce the overall system power consumption by keeping the power consuming main radio off most of the time. Clearly, the consumption of the WU receiver must be sufficiently low for such a system to be viable. For comparison, one can think of a typical BLE receiver that consumes 10 mW. If such a receiver was in a small sensor node, and if it was on all the time it would drain the battery quickly. Since in most cases the data traffic is quite low (although this depends on the application) the receiver can be kept off most of the time, and only turned on when there is a need. This is called duty cycling. The question is: how to know when to turn the receiver on? One way is to synchronize all nodes in a network. A receiver would then turn on at specific time instants to check if the data is transmitted. However, maintaining synchronization in a network often results in a significant overhead that leads to increased power consumption. The communication can also be initiated asynchronously, but in this case the transmitter needs to transmit

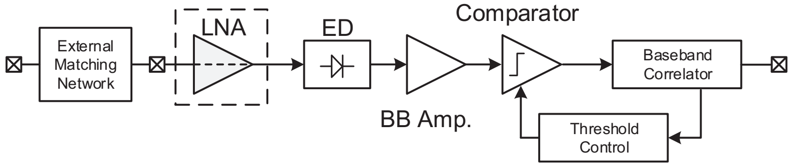



**Figure 2.4** Typical WU receiver block diagram.

continuously until the receiver replies. Now the transmitter needs to consume more on average to initiate communication, but the synchronization overhead is gone. Which option is better depends on a particular case. Either way, assuming that the communication is initiated rarely, the overall power will be dominated by the receiver consumption, as it must be turned on periodically to sample the RF channel. The power consumption is directly proportional to the duty cycle (or the on time) of the receiver. If a 10 mW BLE receiver is turned on for 1 ms every second, in the idealized case the power would be reduced to 10 $\mu$W. A note should be made here that receivers cannot start immediately and that there is always an overhead associated to the start-up that would increase the average consumption. In addition, in the described scenario the worst case latency would be almost 1 s. It can easily be seen that in duty cycled systems there is always a trade-off between consumption and latency. This kind of trade-off can be broken using a wake up receiver. But, as already explained, their power consumption must be brought down to a microwatt level or below.

To achieve the low power levels needed, the WU receivers often employ a very simple architecture and a very simple modulation scheme. In most cases, the RF signal is modulated using the on-off keying (OOK), where the presence of the RF signal corresponds to symbol 1 and the absence of it to 0. Such a signal can be easily demodulated using an envelope detector. A typical WU receiver architecture is presented in Figure 2.4. Envelope detector is followed by a correlator that compares the received sequence to the reference pattern. If the correlator output is higher than a certain value the main receiver is woken up. This threshold can be adjusted to set the ratio of false alarms and missed packets. It can be seen that the only active block operating at RF frequency is the LNA. When it comes to WU receivers the emphasis is usually on minimizing the number of blocks that operate at high frequencies, as higher frequency always mean higher consumption. In some more aggressive approaches even the LNA is omitted, allowing to go down to nanowatt consumption, but this always comes at a price in noise figure

(NF) and sensitivity. The non-linear characteristic of the envelope detector makes the output signal to noise ratio (SNR) dependent on the level of input signal. As a result the equivalent NF increases at lower signal levels, thus quickly degrading performance in the absence of an LNA. Unfortunately, this effect cannot be avoided as some kind of non-linearity is needed to separate the envelope from the RF signal. The situation can be somewhat improved if a high quality input matching network is available to boost the input voltage of the ED, but costly and relatively large off-chip components are needed. Boosting the input voltage using the on-chip passive components is impossible due to a limited Q-factor available.

The second benefit of the simple receiver architecture is the absence of the LO and the frequency synthesizer. Naturally these blocks consume a significant part of the overall power and removing them provides significant savings. This also makes the receiver more agile in the sense that start up interval is much shorter. In standard BLE receivers there are two limiting factors to increasing the start up time. The first one is the crystal oscillator. Such oscillator is necessary in all the NB radios to provide a precise reference from which all the other frequencies are derived. Because this reference needs high precision and low jitter, a high quality resonator, such as a quartz crystal, must be used. Unfortunately, the start-up time of the oscillator is inversely proportional to the Q-factor of the resonator and proportional to the oscillation frequency, resulting in a very slow start-up time. To avoid this, in some cases the reference oscillator is kept on even when the receiver switches off. If a 32 kHz clock is sufficient in the system, keeping it on all the time might cost only 100 nW, in which case the overhead might not be that severe. In most BLE receivers, however, the PLL needs a higher frequency reference that operates at megahertz frequencies and therefore consumes power in the order of microwatts. In these cases keeping the quartz oscillator always on would dominate the receiver consumption and is commonly avoided. The second limit to fast start-up is the loop bandwidth of the PLL. The lower the bandwidth of the PLL the longer it takes for the output frequency to settle, and the reception is not possible until the LO signal is stable. The settling time can be decreased by increasing the bandwidth, but this comes with increased phase noise of the PLL, which might limit the receiver performance. Finally, the simplest way to make the receiver agile is to entirely avoid LO generation. This doesn't come for free, and as a consequence, WU receivers based on an ED usually have poor selectivity and interference rejection (unless a sharp external filter is used).

**Table 2.2** Performance comparison of WU receivers

| Ref. | Sens. [dBm] | Cons. [$\mu$W] | Eff. [nJ/b] | Data Rate [kb/s] | Freq. [MHz] | Supply [V] | Mod. |
|---|---|---|---|---|---|---|---|
| [19] | −69 | 0.0045 | 0.015 | 0.3 | 113 | 0.4 | OOK |
| [20] | −71 | 2.4 | 0.120 | 20 | 868 | 1 | OOK |
| [21] | −65 | 10 | 0.100 | 100 | 2400 | 0.5/1* | OOK |
| [22] | −82 | 415 | 0.830 | 500 | 2400 | 1.2 | IR–PPM |
| [23] | −71 | 0.0074 | 0.037 | 0.2 | 433 | 1/0.6* | OOK |
| [24] | −80.5 | 0.0061 | 0.183 | 0.033 | 109 | 0.4 | OOK |
| [25] | −83 | 3 | 47 | 0.064 | 868 | 2.5 | OOK |
| [26] | −72 | 52 | 0.500 | 100 | 2000 | 0.5 | OOK |
| [27] | −41 | 0.098 | 0.980 | 100 | 915 | 1.2 | OOK |
| [28] | −45.5 | 0.116 | 0.009 | 12.5 | 403 | 1.2/0.5* | OOK |
| [29] | −70 | 44 | 0.220 | 200 | 410 | 1 | FSK |
| [30] | −59 | 0.236 | 0.028 | 8.192 | 2400 | 1/0.5* | BLE BC |
| [31] | −100.5 | 400 | 80 | 5 | 1900 | 0.9 | OOK |
| [32] | −81 | 123 | 1.23 | 100 | 915 | 1 | OOK |
| [33] | −65 | 2500 | 2.5 | 1000 | 915 | 0.8 | OOK |
| [34] | −87 | 44.2 | 0.884 | 50 | 925 | 0.7 | OOK |
| [35] | −75 | 350 | 0.180 | 2000 | 2400 | 0.65 | BFSK |
| [36] | −97 | 99 | 9.9 | 10 | 2400 | 0.5 | OOK |
| [37] | −83 | 227 | 0.227 | 1000 | 2400 | 0.6 | OOK |

*Analog/digital supply.

A comparison of recent state of the art WU receivers is given in Table 2.2. A large variety of operating frequencies, data rates and efficiencies can be observed. A large number of implementations is targeting the license free 2.4 GHz ISM band. As already stated, most of them are using OOK modulation, with several exceptions using PPM (pulse position modulation) and FSK. Power consumption varies from 2.5 mW all the way down to 4.5 nW. Different architectural and circuit techniques are used to arrive to such low power levels.

The receivers from [22, 26, 36] use a so called "uncertain IF" architecture. The name comes from the fact that the LO frequency is calibrated to be within a given range, and is not as precise as in conventional receivers, making the exact IF unknown. Low power free running oscillators are used to generate the LO. All of them are mixer first receivers that place gain stages at IF instead of RF in order to lower consumption. The IF amplifiers are wideband (100 MHz in [26]) as they must cover the whole range of possible IF frequencies. For interferer suppression, an external bulk acoustic wave (BAW) filter is used in [26], while [36] uses a series of n-path filters. A polyphase IF filter is used in [22] to provide rejection at the image frequency.

Instead of OOK, in [22] a spread spectrum technique is used. The signal is modulated using short pulses with a bandwidth of 12.5 MHz combined with PPM. The receiver can operate using a frequency reference with up to $\pm 0.5\%$ error, making it possible to remove the quartz crystal from the system, reducing both cost and size. However, the power consumption of 415 $\mu$W is higher than most other WU receivers. The implementation from [25] is a super-heterodyne receiver that uses bit-level duty cycling of all RF blocks, allowing it to reduce power consumption from 100 $\mu$W to only 3 $\mu$W. All circuits are optimized for fast start-up to minimize the overhead coming from duty cycling. One downside is the reduction of sensitivity, since the receiver is not exploiting the full energy of each symbol. The only FSK receivers are described in [29, 35]. Receiver from [35] is a super-regenerative receiver that injects the received signal into a VCO. Depending on the received frequency and the resonance frequency of the VCO the oscillations will build up faster or slower. This approach is used to distinguish between the two FSK symbols. A low IF approach is used in [29], where a low power technique for LO generation is presented. A ring oscillator that produces 9 phases is locked onto a reference oscillator using injection locking. These 9 phases are then combined to produce the LO at a frequency that is 9 times higher than the reference frequency. This approach proves to be more efficient than using an oscillator that operates directly at RF. Another super-regenerative receiver is reported in [31], here used to detect an OOK signal. This receiver achieves the highest sensitivity of all the implementations reported here. The SRR receivers achieve good sensitivity for a given power, but their consumption cannot be lowered beyond a certain point as they require an RF oscillator.

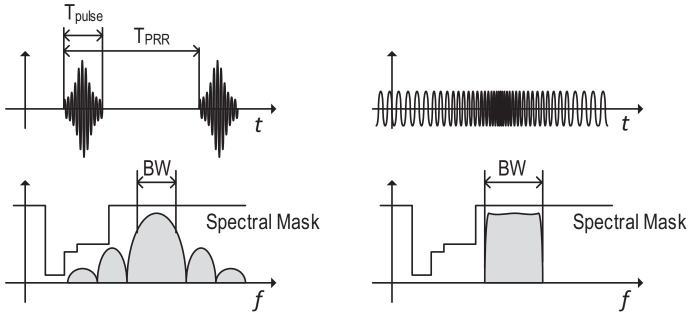
Implementations from [27, 28] were among the first that managed to reduce the power to the level of 100 nW, allowing to supply these receivers directly from an energy harvesting source. However, in these first attempts the sensitivity was quite low, in the order of −40 dBm, limiting the range and scope of use of such receivers. In [30] sensitivity was improved, while maintaining similar power consumption. Finally, receivers from [19, 23, 24] all consume below 10 nW and achieve sensitivities close to −70 dBm. One of the enablers for such low consumption is the low frequency of operation between 100 MHz and 400 MHz. At this frequencies high-Q external passive components can be used to provide large passive voltage gain before the envelope detector. Still, the sensitivity improvement mainly comes from data rates below 0.2 kb/s. In [19] the signaling speed is only 15 b/s. Assuming the wake up sequence is 15 bits long it would take 1 s to wake up the main receiver. In all of the mentioned cases low power and decent sensitivity are traded for long wake up time and increased receiver size. These WU receivers could be compared to a BLE receiver at a 0.1% duty cycle, that would be turned on for 1 ms each second. In a worst case scenario with continuous transmission, this leads to 1 s latency. Referring to the lowest power BLE receiver from Table 2.1, this receiver would consume an average power of approximately 1 $\mu$W, which is still 2 orders of magnitude above the WU receiver. In return the BLE receiver provides better sensitivity.

Different performance trade-offs can be observed in the listed WU receivers. It is important to notice that it is impossible to achieve low power, good sensitivity and high speed at the same time. WU receivers tend to sacrifice all other aspects in order to minimize power. This is likely why they haven't been widely adopted by the industry so far and remain only a subject of academic research. Various other aspects such as selectivity and interference rejection must be considered before these kind of receivers could find use in practical applications.

## 2.3 Ultra-Wideband Communications

The ultra wideband signals are defined as signals whose $-10$ dB bandwidth is either larger than 20% of the carrier frequency, or at least 500 MHz. Historically speaking UWB is one of the oldest wireless technologies – some of the first attempts to communicate over the air were done using short pulses generated by a spark gap transmitter. Today, UWB is mainly used for wireless sensing, radars and localization. The UWB radios became popular again from the communications perspective owing to several different reasons. Perhaps the most obvious one is that large bandwidth can accommodate large data rates. The UWB can be used to transmit large quantities of data over short distances in unlicensed parts of the spectrum. For security and military applications UWB is attractive because of the low power spectral density that makes the signal difficult to intercept and jam. When it comes to low power communications UWB is interesting because it offers potential for miniaturization and low power consumption, owing to the simple radio architecture, as well as robustness to interference and multipath fading.

There are different communication schemes that implement UWB, two are important with regards to wireless sensor networks and IoT. These are the frequency modulated UWB (FM-UWB) and the impulse radio UWB (IR-UWB). The two modulation schemes are illustrated in time and frequency domain in Figure 2.5. The IR-UWB uses short pulses in time domain, the shorter the pulses are the larger is the signal bandwidth. Some form of pulse




(a) (b)

**Figure 2.5** Ultra wideband communication schemes, IR-UWB (a) FM-UWB (b).

shaping is usually employed to reduce the side lobes and provide better frequency characteristics. Since the pulse is only present for a short period of time, probability of detection and interfering with other signals is low, making the IR-UWB fairly robust.

The FM-UWB can be seen as a direct frequency domain approach where a slow moving RF carrier is sweeping a large frequency range. Compared to IR-UWB, in this case a continuous signal is transmitted, providing an almost ideal rectangularly shaped spectrum. Nice spectral properties of FM-UWB make it easier to spread the available spectrum into channels. The downside of continuous transmission is that the receiver and transmitter cannot be duty cycled at the symbol level (at least not without a penalty in sensitivity). When it comes to the radio implementation, the FM-UWB generally requires a simpler architecture that consequently allows for lower peak power consumption. The FM-UWB will be studied in detail in the following chapters, while the remainder of this section presents main characteristics of the IR-UWB.

### 2.3.1 Impulse Radio UWB

As explained, the IR-UWB uses a sequence of pulses to convey information. However, the pulses themselves can be modulated in different ways. Just like in the case of NB radios OOK can be used. The presence of a pulse then corresponds to one symbol and the absence to the other. A second way to modulate pulses is to use PPM, where two or more time windows are associated to different symbols. The receiver then detects energy in each window in order to find the pulse and decode the symbol. Both of these approaches are widely used, mainly owing to the simplicity of the receiver.

The LO generation can be completely avoided and a simple envelope detector used for demodulation. The advantage of the PPM is that a pulse is present for every symbol, the energy is then integrated in the two timing windows (for binary PPM) and simply compared, while some sort of threshold search and track algorithm must be used for OOK. The advantage of the OOK is lower PSD for the same energy per pulse and pulse repetition ratio (PRR). A third option is to use PSK for pulse modulation. However, this modulation was rarely used in combination with the IR-UWB as it requires a coherent demodulator which makes the receiver more complex. The last option found in literature is the FSK. Some of the spectral properties in this case can be controlled through the FSK modulation index. When it comes to performance it is equivalent to PPM, except that instead in time the integration is done in two frequency bands. Although complexity is generally similar to that of OOK and PPM [65], this type of modulation was rarely used in the literature.

Unlike with most NB radios, the output power of UWB radios is quite constrained. This is done to prevent the UWB radios from interfering with higher priority spectrum users (WiFi, BT etc.). The average output PSD of a UWB device must not exceed $-41.3\,\mathrm{dBm/MHz}$. This imposes a limit on the energy per pulse and the pulse repetition rate. In order to increase the link budget the output power cannot be simply increased, the PRR must be scaled accordingly in order to avoid violating the spectrum mask, effectively imposing the limit on the maximum data rate. Care should also be taken when interpreting sensitivity of IR-UWB receivers. Sensitivity is defined as the minimum power of the signal at the receiver input for which a certain bit error rate (BER) can be achieved. For low power receivers the required BER is usually $10^{-3}$. For NB radios the average signal power doesn't change with the symbol duration (or data rate) because the signal is continuous. However, the average power of the IR-UWB signal will reduce if the symbol duration decreases. Even though the sensitivity improves, the total range and the link budget stay the same. Since the average transmit power decreases as well, it is possible to increase energy per pulse on the transmitter side without violating the spectrum mask. This is sometimes referred to as the duty cycle gain. For this reason some authors report sensitivity normalized to data rate. Another thing to note is that for the case of IR-UWB increasing symbol duration doesn't increase energy per bit, so long as the pulse duration is unchanged.

A typical IR-UWB transmitter is shown in Figure 2.6. Even though the whole PLL is shown it is not necessary to use it. Given the large bandwidth of the signal, carrier frequency doesn't need to be precise. Therefore, a free running oscillator, such as a calibrated ring oscillator, is sufficient. In some

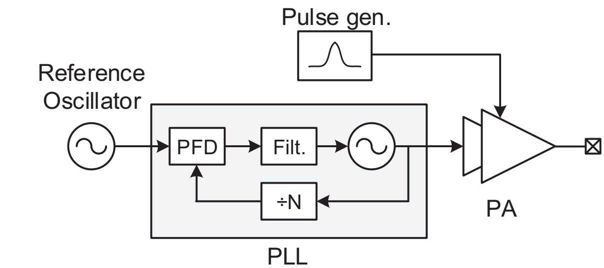



**Figure 2.6** IR-UWB transmitter block diagram.

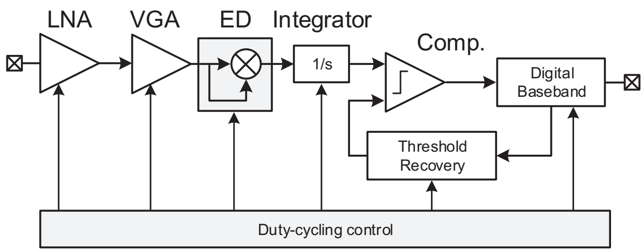



**Figure 2.7** IR-UWB OOK/PPM receiver block diagram.

cases even a tuned delay circuit can be used to generate a pulse. Precise frequency control is mainly needed if FSK is used for pulse modulation. Amplitude control in the PA is not necessary, but is often used to improve the spectrum shape. Gaussian pulse shaping is typically used and since the Fourier transform of a Gaussian pulse is also Gaussian, the resulting spectrum will have a Gaussian shape. Proper pulse shaping helps not only to lower the side lobes, but also to make the spectrum more flat, allowing higher output power without violating the mask. Amplitude modulation adds a degree of complexity and makes the transmitter less energy efficient, but the benefits often outweigh the downsides. The fact that the pulse is usually much shorter than the symbol duration can be exploited to duty cycle the transmitter. The circuits can easily be kept off almost all the time and only switched on to transmit a pulse, drastically reducing the average power consumption of the transmitter. The requirement is simply to optimize circuits for fast start-up.

A generic receiver architecture of an OOK/PPM modulated IR-UWB receiver is given in Figure 2.7. The envelope detector based architecture resembles that of the standard WU receiver. The main difference is that all the circuits need to support a much larger bandwidth. As a general rule, these circuits consume a larger amount of power in order to provide the same gain and noise figure as the narrow-band circuits. This is the main disadvantage of UWB radios compared to NB radios.

Using the same reasoning as for the transmitter, one might also think about duty cycling the receiver. The problem on the receiver side is that it is not a priori known when the pulses are going to arrive. Before duty cycling can be applied, the receiver must synchronize to the incoming pulses. Usually the preamble of the packet is used to achieve synchronization so that the receiver can be duty cycled while receiving the data payload. Such a scheme is useful only if the data payload is sufficiently long to provide significant overall power savings. A different scheme is proposed in [43], where the receiver is always duty cycled. To accommodate this the preamble is done in a specific way – the 31 bit synchronization sequence is repeated 19 times. The receiver is integrating the envelope of the signal over a certain time window. Since the integration time is much shorter than the symbol time, it might happen that there is no overlap between the transmitted pulses and the receiver integration time. If this occurs the time reference of the receiver is shifted. The process continues until the receiver correctly detects the synchronization sequence. After that the correct pulse timing is known for the data payload. The downside of this approach is that the synchronization sequence is longer and that in the worst case the receiver will spend at least the same amount of energy for synchronization as in the case without duty cycling. The average energy needed for synchronization should still be lower with the proposed data format from [43].

Selected IR-UWB receivers are compared in Table 2.3. A large variety of performances can be observed, with the data rates going from 30 kb/s up to 500 Mb/s. The implementations interesting for WSN applications are generally in the region between 100 kb/s and 1 Mb/s. Although high speed IR-UWB radios come with highest efficiencies (even compared to NB WU radios), high peak power consumption might pose a problem in a battery powered device, as large peak current might damage the battery. Moderate data rates with low to moderate consumption are a preferred choice in such scenarios. Most implementations are using OOK and PPM, and some implementations come with a modified custom modulation in order to improve performance. The S-OOK modulation, introduced in [41], stands for synchronous OOK. In this type of modulation a leading pulse is introduced for each symbol. This simplifies synchronization on the receiver side as the position of the information carrying pulse is known with respect to the leading pulse. It also allows to remove a precise timing reference from the receiver, since it simply needs to lock to reference pulses (frequency drift

**Table 2.3** Performance comparison of IR-UWB receivers

| Ref. | Sens. [dBm] | Cons. [mW] | Eff. [pJ/b] | Data Rate [Mb/s] | Freq. [GHz] | BW [MHz] | Mod. |
|---|---|---|---|---|---|---|---|
| [38] | −59 | 13.3 | 26.6 | 500 | 7.875 | 1250 | OOK |
| [39] | −50 | 13 | 130 | 100 | 4 | 2000 | OOK |
| [40] | −76.5 | 0.75 | 375 | 2 | 4.35 | 500 | OOK |
| [41] | −60 | 1.64 | 1640 | 1 | 3.8 | 500 | S–OOK |
| [42] | −74 | 21 | 21000 | 1 | 3–4 | <1000 | FH–OOK |
| [43] | −70 | 4.2 | 840 | 5 | 7.25–8 | 1000 | PPM |
| [43] | −87 | 4.2 | 4200 | 0.1 | 7.25–8 | 1000 | PPM |
| [44] | −65.8 | 30.5 | 305 | 100 | 3.1–4.9 | 1500 | RA–OOK |
| [45] | −67 | 0.406 | 1230 | 0.03 | 9.8 | 1000 | PPM |
| [46] | −87* | 0.110 | 800 | 0.14 | 3.5–4.5 | 500 | OOK |
| [47] | −42** | 18 | 180 | 10 | 3–5 | 500 | OOK |
| [48] | −76 | 22.5 | 1400 | 16 | 3–5 | 500 | PPM/OOK |
| [49] | −70 | 6.6 | 320 | 20.8 | 5 | 1000 | OOK |
| [50] | −99* | 35.8 | 2500 | <16.7 | 3–5 | 500 | PPM |
| [51] | −88 | 1.3 | 1300 | 1 | 4.85 | 600 | OOK |

*At 100 kb/s.
**Estimated.

of an on-chip oscillator should be negligible over one symbol period). The downside of S-OOK is the increased PRR, as more than one pulse is now needed per symbol, effectively decreasing the maximum allowed transmit power. The transceiver described in [42] uses frequency hopping (FH) OOK. each transmitted pulse is shifted in frequency, spreading the spectrum of the transmitted signal and lowering the PSD. In this way a higher output power can be achieved and link budget can be extended while conforming to the PSD limits. The RA-OOK (random alternate OK) presented in [44] is a simple modification of OOK that improves the spectral properties of the signal. By randomizing phase of the pulses the spectral lines in the output spectrum that might appear due to periodicity of the pulses are avoided. In the same implementation symbol level duty cycling is replaced with a burst level duty cycling. The authors have recognized the difficulty of performing duty cycling at a higher PRR, typically above 10 MHz. This is equivalent to sending very small packets of data and performing packet level duty cycling as is generally done. Aggressive duty cycling of the entire chain is used in the receiver from [40]. Even the bias circuits are on during only 3.9% of the time. Unfortunately, there is power overhead associated to the duty cycle control circuits that cannot be avoided, but the receiver still achieves one the best efficiencies among the medium data rate devices. Similarly, symbol level duty cycling is employed in all the receivers from [45–49]. The implementation reported in [50] maintains similar efficiency over three decades of data rates, with leakage currents degrading performance at very low data rates. The transmitter from [49] uses digital delay cells for pulse generation. These delay cells are calibrated using a delay locked loop and a crystal oscillator. Once calibrated, the transceiver can practically operate without a crystal reference. An effort was also made at a higher level to synchronize IR-UWB radios at a protocol level in order to avoid the use of crystal oscillators [46].

All together, the IR-UWB seems like a promising technique for WSN and IoT types of applications offering a wide range of performance while maintaining very low energy per bit. The main question currently is how to maximize savings from symbol level duty cycling and adapt protocols to minimize dependence on crystal clocks in order to allow further miniaturization of future sensor nodes. Concepts have been proven to work, but the technology still needs to mature before it can be adopted by the industry.

## 2.4 Concluding Remarks

Many different low power radios have been been developed, the aim of this chapter is to present those that target a similar applications space as the FM-UWB, meaning similar data rate and power consumption. All the radios presented in the previous sections are shown together in Figure 2.8 that compares the data rate and power consumption. Three regions can be

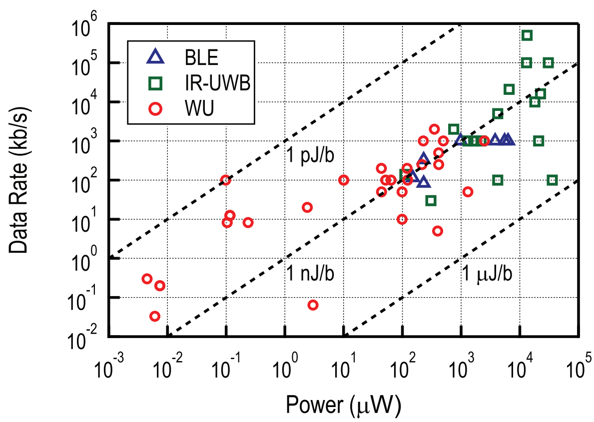



**Figure 2.8** Low power receivers, data rate vs. power consumption.

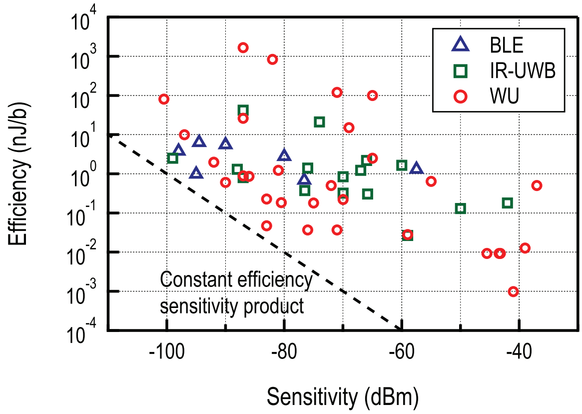



**Figure 2.9** Low power receivers, sensitivity vs. efficiency.

differentiated, WU receivers consume the least, and occupy the left part of the graph. The IR-UWB receivers consume the highest peak power and are mainly located in the right part of the graph. Finally, the BLE receivers are located between the two. A general trend that higher data rates require higher power consumption can be easily observed, if we focus on constant efficiency lines, we can see that most implementations are located close the 1 nJ/b, with a few exceptions approaching 1 pJ/b.

Other than data rate, power consumption is also affected by sensitivity. Sensitivity itself is affected by the data rate as decreasing the data rate increases symbol duration, which consequently increases energy per bit and therefore sensitivity. At the same time sensitivity is dependent on the receiver noise figure. Lowering the NF to improve sensitivity requires more power from the LNA, which is often the dominant block in a low power receiver. Efficiency, defined as the ratio of power consumption and data rate, captures both of these effects when compared against sensitivity. The same receivers are shown in efficiency vs. sensitivity graph in Figure 2.9. Here, a product of efficiency and sensitivity can be regarded as a kind of figure of merit (albeit with some reserve). Once the power consumption is normalized to the symbol duration, the three regions vanish and regardless of the type of receiver, similar performance seems to be achievable. To improve sensitivity we must either improve the receiver NF, which costs additional power, or communicate more slowly, and both means increase energy per bit.

This is off course just a part of the whole story. Many other aspects play an important role in receiver performance. Carrier frequency is one of them, as typically circuit consumption grows with frequency. Looking at an LNA as an example, achieving the same gain and NF requires more power at higher frequencies. Better, but also larger components are available at lower frequencies, allowing better matching networks. Most of the wake up receivers operate in the sub-GHz range, which contributes to their consumption. Such low consumption cannot be achieved in the 4–10 GHz range where most of the IR-UWB receivers are operating. The second important aspect is the dynamic range, or linearity of the receiver. As an example, the consumption of an LNA can be decreased by lowering its supply voltage. This results in lower power consumption, but it also reduces headroom and consequently the compression point. In an environment where multiple devices are present, a signal of one radio will interfere with another. If a receiver is easily saturated by the interfering signal it will be impossible to use it in such scenarios.

To understand all advantages of a certain communication scheme one must look beyond just a few parameters. When compared to standard modulations, FM-UWB is inherently penalized in terms of to sensitivity. For the same energy per bit, the BER of FM-UWB is by construction worse than that of the standard FSK. Instead it offers more robustness in realistic environments (in the presence of multipath fading and interferers) and provides a high potential for miniaturization. Both of these properties are highly important in the IoT and WSN applications, and guarantee that the FM-UWB will find its place among the existing radios.

## References

[1] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of things (iot): A vision, architectural elements, and future directions," *Future Generation Computer Systems*, vol. 29, no. 7, pp. 1645–1660, 2013.

[2] *SX1276/77/78/79 Datasheet*, Semtech, 2019.

[3] T. Sano, M. Mizokami, H. Matsui, K. Ueda, K. Shibata, K. Toyota, T. Saitou, H. Sato, K. Yahagi, and Y. Hayashi, "A 6.3 mW BLE transceiver embedded RX image-rejection filter and TX harmonic-suppression filter reusing on-chip matching network," in *2015 IEEE International Solid-State Circuits Conference – (ISSCC) Digest of Technical Papers*, Feb. 2015, pp. 1–3.

[4] B. Razavi, *RF microelectronics*. Prentice hall New Jersey, 2011.

[5] A. Sai, H. Okuni, T. T. Ta, S. Kondo, T. Tokairin, M. Furuta, and T. Itakura, "A 5.5 mW ADPLL-Based Receiver With a Hybrid Loop Interference Rejection for BLE Application in 65 nm CMOS," *IEEE*

*Journal of Solid-State Circuits*, vol. 51, no. 12, pp. 3125–3136, Dec. 2016.

[6] Y. Liu, X. Huang, M. Vidojkovic, A. Ba, P. Harpe, G. Dolmans, and H. d. Groot, “A 1.9 nj/b 2.4 ghz multistandard (Bluetooth Low Energy/Zigbee/IEEE802.15.6) transceiver for personal/body-area networks,” in *2013 IEEE International Solid-State Circuits Conference Digest of Technical Papers*, Feb. 2013, pp. 446–447.

[7] *PSoC 63 with BLE Datasheet*, Cypress, 2019.

[8] *DA14580 Datasheet*, Dialog Semiconductor, 2014.

[9] *RSL10 Datasheet*, ON Semiconductor, 2018.

[10] A. H. M. Shirazi, H. M. Lavasani, M. Sharifzadeh, Y. Rajavi, S. Mirabbasi, and M. Taghivand, “A 980 $\mu$W 5.2 dB-NF current-reused direct-conversion bluetooth-low-energy receiver in 40 nm CMOS,” in *2017 IEEE Custom Integrated Circuits Conference (CICC)*, Apr. 2017, pp. 1–4.

[11] M. R. Abdelhamid, A. Paidimarri, and A. P. Chandrakasan, “A $-80$ dBm BLE-compliant, FSK wake-up receiver with system and within-bit dutycycling for scalable power and latency,” in *2018 IEEE Custom Integrated Circuits Conference (CICC)*, Apr. 2018, pp. 1–4.

[12] A. Alghaihab, J. Breiholz, H. Kim, B. Calhoun, and D. D. Wentzloff, “A 150 $\mu$W $-57.5$ dBm-Sensitivity Bluetooth Low-Energy Back-Channel Receiver with LO Frequency Hopping,” in *2018 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, June 2018, pp. 324–327.

[13] *CC2540 Datasheet*, Texas Instruments, 2013.

[14] *nRF51822 Product Specification*, Nordic Semiconductor, 2014.

[15] *nRF52832 Product Specification*, Nordic Semiconductor, 2017.

[16] *EM 9301 Datasheet*, EM Microelectronic, 2013.

[17] *TC35679 Datasheet*, Toshiba, 2018.

[18] *TC35681 Datasheet*, Toshiba, 2019.

[19] H. Jiang, P. H. P. Wang, L. Gao, P. Sen, Y. H. Kim, G. M. Rebeiz, D. A. Hall, and P. P. Mercier, “A 4.5 nW wake-up radio with $-69$ dbm sensitivity,” in *2017 IEEE International Solid-State Circuits Conference (ISSCC)*, Feb. 2017, pp. 416–417.

[20] C. Hambeck, S. Mahlknecht, and T. Herndl, “A 2.4 $\mu$W Wake-up Receiver for wireless sensor nodes with $-71$ dbm sensitivity,” in *2011 IEEE International Symposium on Circuits and Systems (ISCAS)*, May 2011, pp. 534–537.

[21] K.-W. Cheng, X. Liu, and M. Je, “A 2.4/5.8 GHz 10 $\mu$W wake-up receiver with $-65$/$-50$ dBm sensitivity using direct active rf detection,”

in *Solid State Circuits Conference (A-SSCC), 2012 IEEE Asian*, Nov. 2012, pp. 337–340.

[22] S. Drago, D. Leenaerts, F. Sebastiano, L. Breems, K. Makinwa, and B. Nauta, "A 2.4 GHz 830 pJ/bit duty-cycled wake-up receiver with $-82$ dBm sensitivity for crystal-less wireless sensor nodes," in *Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2010 IEEE International*, Feb. 2010, pp. 224–225.

[23] J. Moody, P. Bassirian, A. Roy, N. Liu, N. S. Barker, B. H. Calhoun, and S. M. Bowers, "Interference Robust Detector-First Near-Zero Power Wake-Up Receiver," *IEEE Journal of Solid-State Circuits*, pp. 1–14, 2019.

[24] P. P. Wang, H. Jiang, L. Gao, P. Sen, Y. Kim, G. M. Rebeiz, P. P. Mercier, and D. A. Hall, "A 6.1-nW Wake-Up Receiver Achieving $-80.5$-dBm Sensitivity Via a Passive Pseudo-Balun Envelope Detector," *IEEE Solid-State Circuits Letters*, vol. 1, no. 5, pp. 134–137, May 2018.

[25] H. Milosiu, F. Oehler, M. Eppel, D. Fruehsorger, S. Lensing, G. Popken, and T. Thoenes, "A 3- $\mu$W 868-MHz wake-up receiver with $-83$ dBm sensitivity and scalable data rate," in *2013 Proceedings of the ESSCIRC (ESSCIRC)*, Sep. 2013, pp. 387–390.

[26] N. M. Pletcher, S. Gambini, and J. Rabaey, "A 52 $\mu$W wake-up receiver with $-72$ dBm sensitivity using an uncertain-IF architecture," *IEEE Journal of Solid-State Circuits*, vol. 44, no. 1, pp. 269–280, Jan. 2009.

[27] N. Roberts and D. Wentzloff, "A 98 nw wake-up radio for wireless body area networks," in *2012 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, June 2012, pp. 373–376.

[28] S. Oh, N. E. Roberts, and D. D. Wentzloff, "A 116 nw multi-band wake-up receiver with 31-bit correlator and interference rejection," in *Proceedings of the IEEE 2013 Custom Integrated Circuits Conference*, Sep. 2013, pp. 1–4.

[29] J. Pandey, J. Shi, and B. Otis, "A 120 $\mu$w mics/ism-band fsk receiver with a 44 $\mu$w low-power mode based on injection-locking and 9x frequency multiplication," in *2011 IEEE International Solid-State Circuits Conference*, Feb. 2011, pp. 460–462.

[30] N. E. Roberts, K. Craig, A. Shrivastava, S. N. Wooters, Y. Shakhsheer, B. H. Calhoun, and D. D. Wentzloff, "26.8 A 236 nW $-56.5$ dBm-sensitivity bluetooth low-energy wakeup receiver with energy harvesting in 65 nm CMOS," in *2016 IEEE International Solid-State Circuits Conference (ISSCC)*, Jan. 2016, pp. 450–451.

[31] B. Otis, Y. H. Chee, and J. Rabaey, "A 400 $\mu$W-RX, 1.6 mW-TX super-regenerative transceiver for wireless sensor networks," in *Solid-State Circuits Conference, 2005. Digest of Technical Papers. ISSCC. 2005 IEEE International*, Feb. 2005, pp. 396–606 Vol. 1.

[32] X. Huang, P. Harpe, G. Dolmans, and H. de Groot, "A 915 MHz ultra-low power wake-up receiver with scalable performance and power consumption," in *ESSCIRC (ESSCIRC), 2011 Proceedings of the*, Sep. 2011, pp. 543–546.

[33] D. Daly and A. Chandrakasan, "An Energy-Efficient OOK Transceiver for Wireless Sensor Networks," *IEEE Journal of Solid-State Circuits*, vol. 42, no. 5, pp. 1003–1011, May 2007.

[34] T. Abe, T. Morie, K. Satou, D. Nomasaki, S. Nakamura, Y. Horiuchi, and K. Imamura, "An ultra-low-power 2-step wake-up receiver for IEEE 802.15.4g wireless sensor networks," in *2014 Symposium on VLSI Circuits Digest of Technical Papers*, June 2014, pp. 1–2.

[35] J. Ayers, K. Mayaram, and T. Fiez, "An Ultralow-Power Receiver for Wireless Sensor Networks," *IEEE Journal of Solid-State Circuits*, vol. 45, no. 9, pp. 1759–1769, Sep. 2010.

[36] C. Salazar, A. Cathelin, A. Kaiser, and J. Rabaey, "A 2.4 ghz interferer-resilient wake-up receiver using a dual-if multi-stage n-path architecture," *IEEE Journal of Solid-State Circuits*, vol. 51, no. 9, pp. 2091–2105, Sep. 2016.

[37] L. Jae-Seung, K. Joo-Myoung, L. Jae-Sup, H. Seok-Kyun, and L. Sang-Gug, "13.1 A 227 pJ/b $-83$ dbm 2.4 GHz multi-channel OOK receiver adopting receiver-based FLL," in *Solid- State Circuits Conference – (ISSCC), 2015 IEEE International*, Feb. 2015, pp. 1–3.

[38] S. Geng, D. Liu, Y. Li, H. Zhuo, W. Rhee, and Z. Wang, "A 13.3 mW 500 Mb/s IR-UWB Transceiver With Link Margin Enhancement Technique for Meter-Range Communications," *IEEE Journal of Solid-State Circuits*, vol. 50, no. 3, pp. 669–678, Mar. 2015.

[39] L. Xia, K. Shao, H. Chen, Y. Huang, Z. Hong, and P. Y. Chiang, "0.15-nJ/b 3–5-GHz IR-UWB System With Spectrum Tunable Transmitter and Merged-Correlator Noncoherent Receiver," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, no. 4, pp. 1147–1156, Apr. 2011.

[40] B. Vigraham and P. Kinget, "A self-duty-cycled and synchronized UWB receiver SoC consuming 375 pJ/b for $-76.5$ dBm sensitivity at 2 Mb/s," in *2013 IEEE International Solid-State Circuits Conference Digest of Technical Papers*, Feb. 2013, pp. 444–445.

[41] M. Crepaldi, C. Li, J. R. Fernandes, and P. R. Kinget, “An Ultra-Wideband Impulse-Radio Transceiver Chipset Using Synchronized-OOK Modulation,” *IEEE Journal of Solid-State Circuits*, vol. 46, no. 10, pp. 2284–2299, Oct. 2011.

[42] D. Liu, X. Ni, R. Zhou, W. Rhee, and Z. Wang, “A 0.42-mW 1-Mb/s 3- to 4-GHz Transceiver in 0.18- $\mu \textm$ CMOS With Flexible Efficiency, Bandwidth, and Distance Control for IoT Applications,” *IEEE Journal of Solid-State Circuits*, vol. 52, no. 6, pp. 1479–1494, June 2017.

[43] S. Solda, M. Caruso, A. Bevilacqua, A. Gerosa, D. Vogrig, and A. Neviani, “A 5 Mb/s UWB-IR Transceiver Front-End for Wireless Sensor Networks in 0.13$\mu\hboxm$CMOS,” *IEEE Journal of Solid-State Circuits*, vol. 46, no. 7, pp. 1636–1647, July 2011.

[44] R. Vauche, E. Muhr, O. Fourquin, S. Bourdel, J. Gaubert, N. Dehaese, S. Meillere, H. Barthelemy, and L. Ouvry, “A 100 MHz PRF IR-UWB CMOS Transceiver With Pulse Shaping Capabilities and Peak Voltage Detector,” *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 64, no. 6, pp. 1612–1625, June 2017.

[45] J. K. Brown, K. Huang, E. Ansari, R. R. Rogel, Y. Lee, and D. D. Wentzloff, “An ultra-low-power 9.8 GHz crystal-less UWB transceiver with digital baseband integrated in 0.18 $\mu$m BiCMOS,” in *2013 IEEE International Solid-State Circuits Conference Digest of Technical Papers*, Feb. 2013, pp. 442–443.

[46] X. Y. Wang, R. K. Dokania, and A. B. Apsel, “A Crystal-Less Self-Synchronized Bit-Level Duty-Cycled IR-UWB Transceiver System,” *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 60, no. 9, pp. 2488–2501, Sep. 2013.

[47] A. Ebrazeh and P. Mohseni, “A 14 pJ/pulse-TX, 0.18 nJ/b-RX, 100 Mbps, channelized, IR-UWB transceiver for centimeter-to-meter range biotelemetry,” in *Proceedings of the IEEE 2014 Custom Integrated Circuits Conference*, Sep. 2014, pp. 1–4.

[48] D. C. Daly, P. P. Mercier, M. Bhardwaj, A. L. Stone, Z. N. Aldworth, T. L. Daniel, J. Voldman, J. G. Hildebrand, and A. P. Chandrakasan, “A Pulsed UWB Receiver SoC for Insect Motion Control,” *IEEE Journal of Solid-State Circuits*, vol. 45, no. 1, pp. 153–166, Jan. 2010.

[49] A. Mehra, M. Sturm, D. Hedin, and R. Harjani, “A 0.32 nJ/bit noncoherent UWB impulse radio transceiver with baseband synchronization and a fully digital transmitter,” in *2013 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, June 2013, pp. 17–20.

[50] F. S. Lee and A. P. Chandrakasan, "A 2.5 nJ/bit 0.65 V Pulsed UWB Receiver in 90 nm CMOS," *IEEE Journal of Solid-State Circuits*, vol. 42, no. 12, pp. 2851–2859, Dec. 2007.

[51] B. Vigraham and P. R. Kinget, "An ultra low power, compact UWB receiver with automatic threshold recovery in 65 nm CMOS," in *2012 IEEE Radio Frequency Integrated Circuits Symposium*, June 2012, pp. 251–254.

[52] J. Long, W. Wu, Y. Dong, Y. Zhao, M. A. T. Sanduleanu, J. F. M. Gerrits, and G. van Veenendaal, "Energy-efficient wireless front-end concepts for ultra lower power radio," in *IEEE Custom Integrated Circuits Conference, 2008. CICC 2008*, Sep. 2008, pp. 587–590.

[53] J. Pandey and B. P. Otis, "A sub-100 $\mu$W MICS/ISM band transmitter based on injection-locking and frequency multiplication," *IEEE Journal of Solid-State Circuits*, vol. 46, no. 5, pp. 1049–1058, May 2011.

[54] P. J. A. Harpe, C. Zhou, Y. Bi, N. P. van der Meijs, X. Wang, K. Philips, G. Dolmans, and H. de Groot, "A 26 $\mu$w 8 bit 10 ms/s asynchronous sar adc for low energy radios," *IEEE Journal of Solid-State Circuits*, vol. 46, no. 7, pp. 1585–1595, July 2011.

[55] J. Farserotu, J. Baborowski, J. D. Decotignie, P. Dallemagne, C. Enz, F. Sebelius, B. Rosen, C. Antfolk, G. Lundborg, A. Björkman, T. Knieling, and P. Gulde, "Smart skin for tactile prosthetics," in *2012 6th International Symposium on Medical Information and Communication Technology (ISMICT)*, Mar. 2012, pp. 1–8.

[56] *IEEE Standard for Local and Metropolitan Area Networks – Part 15.6: Body Area Networks*, 2012.

[57] M. Verhelst, N. V. Helleputte, G. Gielen, and W. Dehaene, "A reconfigurable, 0.13 $\mu$m cmos 110 pJ/pulse, fully integrated IR-UWB receiver for communication and sub-cm ranging," in *2009 IEEE International Solid-State Circuits Conference – Digest of Technical Papers*, Feb. 2009, pp. 250–251,251a.

[58] A. Medi and W. Namgoong, "A high data-rate energy-efficient interference-tolerant fully integrated cmos frequency channelized uwb transceiver for impulse radio," *IEEE Journal of Solid-State Circuits*, vol. 43, no. 4, pp. 974–980, Apr. 2008.

[59] Y. Zheng, Y. Tong, C. W. Ang, Y.-P. Xu, W. G. Yeoh, F. Lin, and R. Singh, "A CMOS carrier-less UWB transceiver for WPAN applications," in *2006 IEEE International Solid State Circuits Conference – Digest of Technical Papers*, Feb. 2006, pp. 378–387.

[60] M. Crepaldi, C. Li, K. Dronson, J. Fernandes, and P. Kinget, “An ultra-low-power interference-robust IR-UWB transceiver chipset using self-synchronizing OOK modulation,” in *2010 IEEE International Solid-State Circuits Conference – (ISSCC)*, Feb. 2010, pp. 226–227.

[61] F. Zhang, A. Jha, R. Gharpurey, and P. Kinget, “An agile, ultra-wideband pulse radio transceiver with discrete-time wideband-IF,” *IEEE Journal of Solid-State Circuits*, vol. 44, no. 5, pp. 1336–1351, May 2009.

[62] L. Liu, T. Sakurai, and M. Takamiya, “A 1.28 mW 100 Mb/s impulse UWB receiver with charge-domain correlator and embedded sliding scheme for data synchronization,” in *2009 Symposium on VLSI Circuits*, June 2009, pp. 146–147.

[63] R. Liu, B. R. Carlton, S. Pellerano, F. Sheikh, D. S. Vemparala, A. Ali, and V. S. Somayazulu, “A 264-$\mu$W 802.15.4a-Compliant IR-UWB Transmitter in 22 nm FinFET for Wireless Sensor Network Application,” in *2018 IEEE Radio Frequency Integrated Circuits Symposium (RFIC)*, June 2018, pp. 164–167.

[64] X. Wang, Y. Yu, B. Busze, H. Pflug, A. Young, X. Huang, C. Zhou, M. Konijnenburg, K. Philips, and H. D. Groot, “A meter-range UWB transceiver chipset for around-the-head audio streaming,” in *2012 IEEE International Solid-State Circuits Conference*, Feb. 2012, pp. 450–452.

[65] D. Barras, “A low power impulse radio ultra-wideband cmos radio-frequency transceiver,” PhD dissertation, ETH Zurich, 2010.