Ultra Low Power Transceiver for Wireless Body Area Networks

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Chapter 2
Review of the State of the Art

Given the wide range of possible applications, low-power short-range transceivers have drawn a lot of attention, both in research and industry. In this chapter, the current state-of-the-art-of transceivers operating in the frequency range from 1 to 10 GHz is reviewed briefly. Given the limited amount of data that is to be exchanged with wireless sensors or actuators, the WBAN transceivers usually implemented a data rate between 100 kb/s and a few Mb/s. Generally, the proposed transceivers can be categorized in three generic groups. First of all, there are conventional narrow-band transceivers which usually operate in the 2.4 GHz ISM band and implement one of the typical WBAN standards ZigBee [24, 60, 62, 64, 104, 109, 147], Bluetooth [26, 34, 36, 57, 67, 119, 123] or bluetooth low energy (BLE) [9, 37, 42, 141]. The second group are wide-band transceivers, which occupy a much larger bandwidth than absolutely necessary for their respective data rates in order to allow for super-regenerative receivers [18, 91, 101, 133, 149]. Finally, the third group are impulse-radio ultra wide-band (IR-UWB) transceivers that transmit extremely short RF pulses, and hence occupy a large bandwidth of several GHz [14, 15, 41, 45, 50, 120, 139, 140, 151].

2.1 Low-Power Narrow-Band Transceivers

Narrow-band transceivers are characterized mainly by their effective usage of the available spectrum, i.e., the signal bandwidth B is on the order of the data rate R. Therefore, the available spectrum can be split up into various channels and so allow for multiple users operating at the same time. This makes these transceivers attractive for commercial applications where inter operability and spectrum sharing are of particular importance. Consequently, the three dominating WBAN standards ZigBee, Bluetooth, and BLE define a narrow-band physical layer which exploit the 2.4 GHz ISM band (2.400–2.4835 GHz) with a different number of channels,[1] as illustrated in Fig. 2.1. Note that the ZigBee standard employs direct sequence spectrum spreading

[1] To be more precise, ZigBee employs the physical layer defined in the IEEE 802.15.4 standard.

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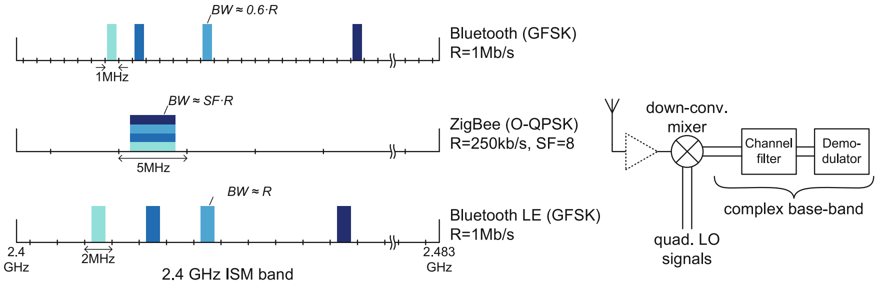

Fig. 2.1 Spectral planning of the typical narrow-band WBAN standards with the typical receiver architecture

(DSSS) to avoid interference, which effectively adds redundancy to the signaling, and hence increases the bandwidth. Increasing the redundancy by the ZigBee spreading factor of $SF = 8$ reduces the required signal-to-noise ratio at the receiver by 9 dB ($10 \cdot \log SF$,) and hence allows more users to operate in the same channel. Therefore, ZigBee transceivers are considered here as narrow-band systems, because the bandwidth B is on the order of $R \cdot SF$. Bluetooth and BLE avoid interferers by frequency hopping, which frequently changes the channel.

Narrow-band systems usually employ digital phase- or frequency modulation techniques such as Gaussian Frequency Shift Keying (GFSK) or Quadrature Phase Shift Keying (QPSK) for signaling. In fact, the Offset–QPSK scheme defined in ZigBee is equivalent to GFSK with a modulation index of $h = 0.5$ [60], and hence also similar to the modulation schemes employed by Bluetooth (GFSK, $h = 0.32$) and BLE (GFSK, $h = 0.5$). These modulation schemes have the advantage that they are spectrally efficient due to their low-modulation index and they provide a constant-envelope signal. The constant RF amplitude makes the system robust against nonlinear distortions and so allows for efficient power amplifiers in the transmitter.

To demodulate narrow-band signals under the presence of adjacent channel interferers, quadrature downconversion into a complex baseband is inevitable. The complex baseband allows for narrow channel filtering and hence for rejection of close-by interferers. Therefore, the essential building blocks of narrow-band receivers are the local oscillator (LO) defining the channel to be demodulated and a quadrature down-conversion mixer.

2.2 Super-Regenerative Wide-Band Transceivers

A lower power consumption can be achieved by using a higher bandwidth for the same data rate, i.e., $B \gg R$. This leads to a far less efficient usage of the radio spectrum, and therefore wide-band transceivers have been mainly proposed for closed systems in an academic environment [18, 91, 101, 133, 149]. These systems usually also employ FSK modulation but with a much larger modulation index ($h \gg 1$) [18, 101, 149], meaning that to transmit binary data symbols, two widely separated frequencies

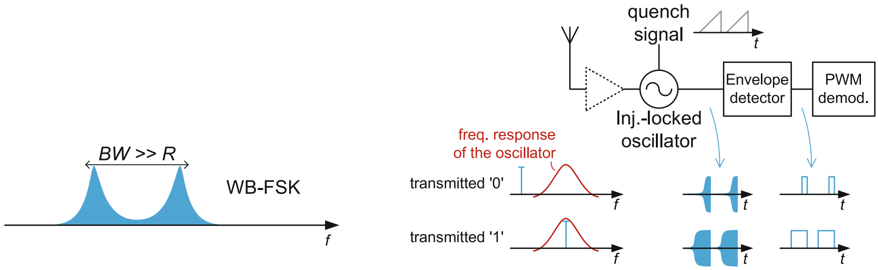

Fig. 2.2 Wide-band FSK (WB-FSK) power spectrum (*left*) and the typical super-regenerative receiver architecture

are transmitted, as shown in Fig. 2.2. The high modulation index allows for a simple, and hence power-efficient super-regenerative receiver architecture. However, this RX architecture is characterized by a poor spectral selectivity, which means that no interferers can be tolerated within a wide bandwidth. For this reason, also super-regenerative transceivers using On Off Keying (OOK) [91, 133] are considered here as wide-band systems.

Super-regenerative receivers employ an extremely simple architecture, which is based on injection locking of an oscillator. The input signal is applied to an oscillator whose resonance frequency is close to the expected incoming tone. Then, the start-up time of the oscillator is highly dependent on whether or not an incoming tone is present, i.e., a tone close to the resonance frequency stimulates the oscillator leading to a low start-up time, as illustrated in Fig. 2.2. By repeatedly ramping up the oscillator, which is referred to as *quenching*, the presence of the tone can be easily is monitored. Changing the resonance frequency oscillator also allows for monitoring tones at different frequencies and hence FSK demodulation, provided that the two FSK tones are sufficiently separated to make a difference in the start-up behavior of the oscillator. Therefore, the spectral selectivity of this demodulation scheme is mainly given by the bandpass characteristic of the oscillator, and hence depends eventually on the quality factor of the resonator. Given the low quality factor achievable in integrated solutions this leads to a poor spectral selectivity of the super-regenerative receiver architecture.

On the other hand, the simplicity of the super-regenerative RX architecture with extremely few blocks operating at RF allows for a very low-power consumption. Also on the transmitter side, both WB-FSK and OOK modulation allow for simple and low-power architectures, i.e., direct modulation of the oscillator or the power amplifier, respectively.

2.3 Impulse-Radio Ultra Wide-Band Transceivers

The third group is formed by impulse-radio ultra wide-band transceivers [14, 15, 41, 45, 50, 120, 139, 140, 151], which often achieve an even lower power consumption than the previous two groups. The DC power advantage of these transceivers can be

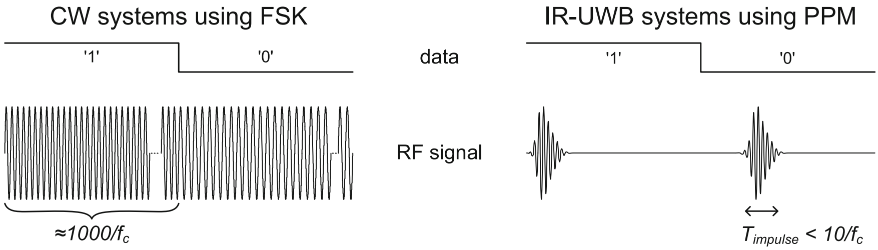

Fig. 2.3 Time-domain diagram of FSK-modulated CW systems (*left*) versus IR-UWB signaling (*right*) which transmits far less periods of the carrier (f_c) per data symbol

best observed in the time domain, as shown in Fig. 2.3. The first two groups essentially employ a continuous wave (CW) carrier signal (1–10 GHz) which is modulated with a low-frequency data signal (≈1 MHz), and hence transmit thousands of RF periods per bit. In contrast to these CW systems, IR-UWB transceivers emit only short pulses per bit, usually comprised less than 10 RF periods. The data are often encoded with pulse position modulation (PPM) or with pulsed FSK. Therefore, the RF section of the transmitter is active only for a short fraction of the time, which leads to a low average power consumption. Once the transmitter and receiver are synchronized, the receiver can be duty cycled as well to reduce the power consumption for low data rates [45, 50].

The short RF pulses with an impulse duration (T_{impulse}) of usually less than 1 ns consequently occupy a very large bandwidth on the order of a few GHz ($\approx 1/T_{\mathrm{impulse}}$). This makes IR-UWB systems robust against narrow-band interferers and frequency-selective fading effects. On the other hand, the tolerance concerning other pulsed interferers depends highly on the synchronization capability. Moreover, the synchronization often dominates the overall RX energy dissipation, especially for short data packets [82, 140].

Although IR-UWB is a relatively new trend in WBAN communications, a standardized physical layer has been already defined (IEEE 802.15.4a) which operates in the frequency band from 3.1 to 10.6 GHz. Moreover, IR-UWB transceivers start to appear in the industry for point-to-point applications [139].

2.4 Comparison

To compare the three groups, Fig. 2.4 shows the sum of the TX and RX power consumption $P_{DC,TX+RX}$ of the relevant low-power transceivers versus their link data rate. The first group of narrow-band TRXs (shown in blue) can be clearly identified at the top with a total power consumption ranging from about 10 to 100 mW. Usually, one order of magnitude less power is consumed by the wide-band TRXs (1–10 mW), which also applies to the two ultra-low data rate TRXs with 5 kb/s not shown in the diagram [91, 101]. In contrast, pulsed TRXs are not distributed

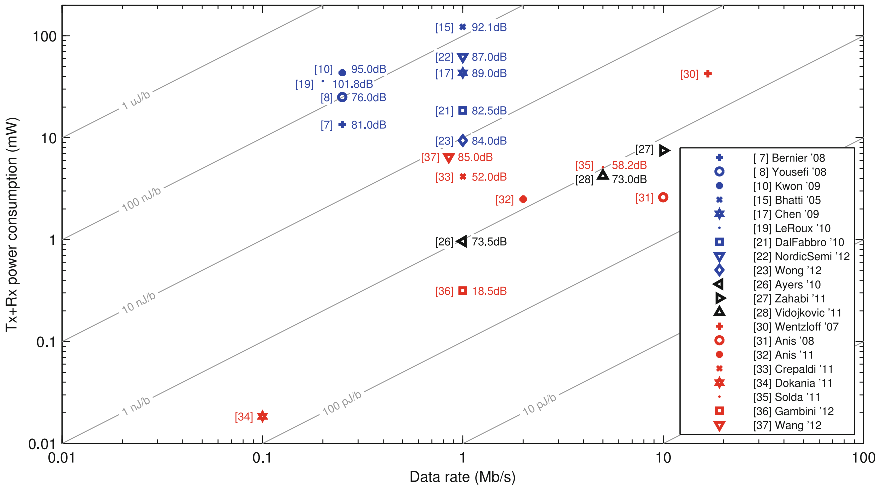

Fig. 2.4 Comparison of recent low-power transceivers considering the sum of TX and RX power consumption (y-axis). Narrow-band, wide-band, and IR-UWB transceivers are distinguished by *blue*, *black* and *red markers*, respectively. The dB-values in the figure denote the link budget of the respective transceiver (P_{out}/P_{sens})

within a characteristic DC power range but rather along a specific Energy-per-bit ratio on the order of 1 nJ/b, i.e., the power consumption of these duty-cycled TRXs scales with the data rate. However, around the typical WBAN data rate of 1 Mb/s the IR-UWB systems can achieve a power consumption of 1–2 order magnitude less than narrow-band TRXs [50].

Apart from the power consumption, an important figure of merit is the link budget (P_{out}/P_{sens}) provided by the transceivers. As mentioned before, a link budget of approximately 80 dB is needed for a robust short-range link [133, 139] taking into account small antennas and other channel imperfections such as fading. The annotated dB-values in Fig. 2.4 show that largest link budgets are obtained by narrow-band transceivers, hence promising the most robust operation. On the other hand, IR-UWB transceivers usually provide a much lower link budget of less than 60 dB due to the low average transmitted power. Although they are also less susceptible to fading effects, IR-UWB systems therefore usually offer a lower communication range than their narrow-band counterparts. Again, the wide-band TRXs fill the gap between the other two systems with link budgets around 70–75 dB.

To conclude, the IR-UWB systems that achieve the lowest power consumption either provide very low link budgets [50] or do not solve the synchronization issue [45]. Wide-band transceivers are promising with respect to power consumption and decent link budget but spectrally inefficient and prone to interference. The best interference tolerance, and hence inter-operability with other services can be achieved by narrow-band transceivers due to the complex baseband channel filtering. Moreover, such transceivers can connect easily to the existing handheld terminals as long as one of the typical WBAN standards is implemented. However, the total power consumption of such systems has to be further reduced in order to provide a higher degree of energy autonomy than the existing solutions.