7

Conclusion

The number of connected devices keeps increasing, but to truly realize the vision of IoT, the vision of thousands of wireless nodes per person, cost, size and consumption of such nodes must be lowered. Cost is related to the size of the node and the number of components. Reducing the number of components is always beneficial, and ideally the whole system would be integrated on a single silicon die. With advances in silicon technologies, various electronic components have become so small that the biggest component on a sensor node is in fact the battery. The smaller it is, the smaller the node will be. Unsurprisingly, the size of the battery is related to its capacity and, consequently, the lower the consumption of a node the smaller the battery and its size.

The consumption of a sensor node is commonly dominated by the consumption of its radio, and lowering the consumption of a radio remains the biggest challenge of the IoT. At the same time, as the number of devices continues to grow, other issues will appear: the increasing number of interferers, scalability problems and latency, to name a few. In this work, we propose FM-UWB as a solution to all of these needs. Inherent interference rejection and support for multiple sub-carrier channels appear to be promising to provide good scalability and robust communication in a progressively noisy environment. Simple receiver and transmitter architectures guarantee low peak power consumption allowing to use smaller batteries. Potential to integrate all components of the transceiver has been demonstrated in the preceding chapters, making FM-UWB the ideal choice for a miniature sensor node.

7.1 Summary of Achievements

As discussed previously, when it comes to power consumption, narrowband receivers inevitably have the advantage. The FM-UWB receiver simply cannot achieve the same sensitivity for a given power consumption, but it brings other benefits to the table. The work presented here continues the trend of lowering the power of FM-UWB transceivers, as illustrated in Figure 7.1. The implemented single-ended AZ-IF receiver further narrows the gap between the narrowband and wideband receivers, but it does so at the cost of lower sensitivity. The implemented quadrature AZ-IF receiver consumes more power, but allows up to four FM-UWB transceivers to share the same RF band, and provides better sensitivity.

The trade-off between sensitivity and efficiency, for different FM-UWB receivers is shown in Figure 7.2. A third axis that could be added, and is often neglected, could be linearity, that is closely related to the ability to distinguish multiple FM-UWB signals.The RF delay line demodulator consumes the most, but still provides the best sensitivity performance, and should be able to support multiple sub-carrier channels [1]. The super regenerative architecture [2, 3], achieves considerable power savings, and relatively good sensitivity, but has a very non-linear demodulator characteristic. Finally, the two architectures proposed in this work are targeting short-range communications, and can therefore withstand lower sensitivity in order to further reduce the

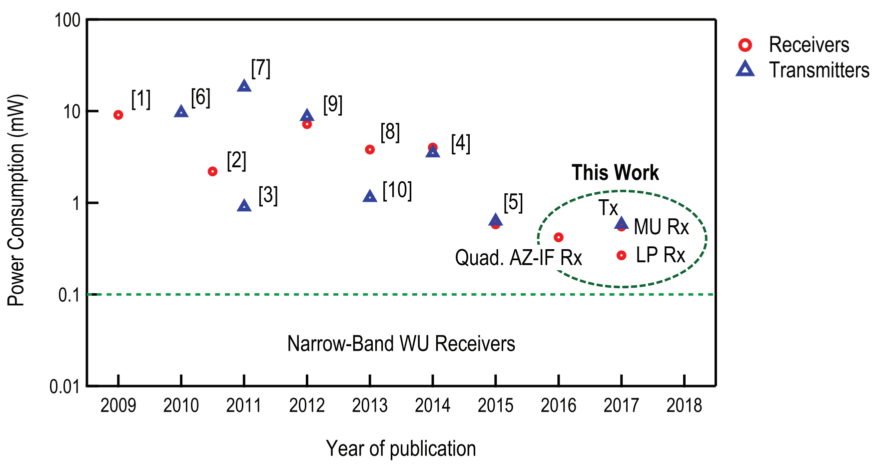

Figure 7.1 Power consumption evolution of implemented FM-UWB transmitters and receivers.

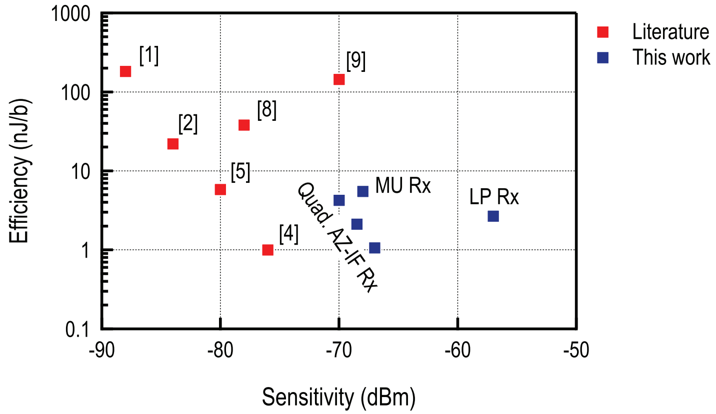

Figure 7.2 Efficiency vs. sensitivity of implemented FM-UWB receivers.

power requirements and provide enough linearity to enable the multi-user communication.

The core of the work focuses on the implementation of an ultra low power FM-UWB transceiver. The design process started with the exploration of options and capabilities of the FM-UWB modulation. Architectures that could yield the desired power reduction have been studied. Finally, different low power circuit techniques have been used to arrive to the achieved power consumption. The main contributions are summarized here:

- The FM-UWB modulation, originally proposed by Gerrits, is a combination of the low modulation index BFSK at baseband, and the large modulation index FM at RF. The concept was first extended to include other baseband modulation types such as MFSK, BPSK and MPSK. Here, a multi-channel transmission, similar to OFDM, is proposed, using a sum of several orthogonal sub-carrier signals to modulate the carrier. The concept allows simultaneous transmission in the same frequency band to multiple receivers and is demonstrated through experiments in Chapter 5.
- The approximate zero-IF architecture is introduced as a modification of the uncertain IF narrowband receiver. The quadrature approximate zero-IF receiver allows to save power while preserving enough FM-AM conversion linearity to allow simultaneous demodulation of multiple input FM-UWB signals. The single-ended version of the receiver further simplifies its architecture reaching the record low power consumption,

but loses sensitivity and loses the capability to distinguish multiple FM-UWB users.

- Aside from power consumption, the implemented transceiver is the first full FM-UWB transceiver that provides the multi-user capability. In this case, four channels with a 100 kb/s data rate are available for simultaneous communication. High resilience to out of band interferers enables reliable communication in the presence of other devices, in particular the devices operating in the 2.4 GHz ISM band.
- High tolerance to large reference frequency offsets is demonstrated, and a circuit that compensates for the mismatch between the transmit and receive clock is proposed. This allows for the integration of the FM-UWB full transceiver without the need for an external high-Q resonator, or any other off-chip components.
- Electronic circuits have been a topic of research for a long time, making it rather difficult to innovate and discover truly new topologies. Most of the used circuits are adaptations and minor modifications of already existing solutions. The two more notable blocks that brought some innovation in this work are the baseband N-path channel filter and the low power DCO. The use of an N-path filter in the baseband allows to easily implement a tunable, high-Q bandpass filter, with relatively low power consumption and simple control. Although N-path filters have been out there for some time, they have never been used in a low power and low frequency application such as this one. Implementing the DCO as a stack of a ring oscillator and a frequency multiplier allowed to run the oscillator at one third of the actual carrier frequency, allowing it to reduce consumption. This was one of the key innovations that led to such low overall consumption of the single-ended approximate zero-IF receiver.

7.2 Future of FM-UWB

The aim of this work was to demonstrate that the FM-UWB answers to most of the modern needs of the IoT, and highlight its advantages compared with conventional narrowband radios. The FM-UWB could develop in several directions:

- Miniaturization – as shown here, the FM-UWB transceiver can operate without a precise frequency reference such as a quartz oscillator. Removing yet another component from a sensor node allows to reduce both size and cost. However, most protocols today rely on some form of time keeping. Efficient asynchronous schemes are needed at a higher level in order to truly exploit such a transceiver and achieve the desired degree of miniaturization.

- Multi-user communication and scalability – a case with 4 sub-carrier channels is demonstrated here, but a different number of channels could be used as well. Techniques that would allow for a larger sub-carrier band and provide more channels can be explored (e.g. higher SC frequencies). At the same time, a trade-off between a number of channels and the data rate per channel can be explored to optimize performance for a particular application. An adaptable solution can be envisioned, allowing the radio to adapt to the changing conditions in a WSN.
- Low power – different methods, not studied here, could allow to find a better trade-off between noise and power consumption. For example, a receiver based on a PLL or a frequency tracking loop has not yet been studied in the context of FM-UWB. New architectural and circuit approaches could enable to further lower the power consumption and potentially achieve the levels of narrowband wake-up receivers.

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