Chapter 4
Hardware Architectures for IR-UWB-Based Transceivers

Abstract Impulse Radio-Ultra-wideband (IR-UWB) is an attractive wireless technology for Wireless Body Area Network (WBAN) applications. Low power transmitter design and low complexity hardware implementation present the possibility of developing sensor nodes with small form factors with high data rate capability. A UWB transceiver is the core unit required in a UWB based WBAN system that provide wireless communications. It determines critical properties of the WBAN, such as data rate and power consumption. This chapter focuses on the hardware implementation of UWB based sensor nodes for WBAN applications. Different realizations of UWB transceiver architectures are described and a critical analysis of their suitability for WBAN applications is presented. In addition, different UWB pulse generation techniques are discussed.

Keywords UWB transmitters · UWB receivers · UWB pulse generation · Hardware implementation · Base band pulse generators · Up-conversion pulse generators · Coherent UWB receivers · Non-coherent UWB receivers · AcR receivers · Transmit-only hardware

4.1 Introduction

UWB transceivers are the main building blocks of any UWB sensor node. UWB transmitters are simple in design and consume a smaller amount of power compared to their narrow band counterparts. An IR-UWB transmitter design consists of an UWB pulse generator. IR-UWB pulse generators can be divided into subcategories, such as base band pulse generators and up-conversion pulse generators.

IR-UWB receivers are more complex in design and consume larger amount of power than IR-UWB transmitters. This poses a challenge to use IR-UWB technology in low-power WBAN devices. It is possible to investigate alternative approaches that lead to incorporating advantages provided by IR-UWB transmitters, while avoiding the disadvantages of using IR-UWB receivers in wearable and

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implantable hardware platforms. IR-UWB receivers can be divided into two major categories: non-coherent receivers and coherent receivers. Suitability of these two types of UWB receivers largely depends on the nature of the application.

This chapter investigates the implementation of UWB based transceivers for WBAN applications. Different design methodologies reported in the literature for the implementation of UWB transmitters and receivers are discussed in this chapter highlighting their advantages and disadvantages.

4.2 UWB Transmitter Design Techniques

The UWB transmitter lies at the core of a UWB based sensor node. Unlike in the case of the narrow band transmitters, the Radio Frequency (RF) portion of the UWB transmitters does not dictate the overall power consumption. Hence, care has to be taken in order to minimize the power consumption of the rest of the transmitter circuitry. This section will analyze some common transmitter design techniques that are available in the literature.

A UWB transmitter design starts with a narrow UWB pulse generator. The earlier versions of the UWB pulse generators used Step Recovery Diodes (SRD) in order to generate the pulses and Schottky diodes for pulse shaping. In this technique, the SRD creates a voltage step function with a very short rise time [1, 2]. A delayed version of this step function is also created by making the step function to propagate through a transmission line. The original step function is combined with the delayed version of itself in order to make a narrow UWB pulse. There are several drawbacks in this method of pulse generation that make this technique less attractive for WBAN applications. The length of the transmission line used in order to obtain the delayed version of the pulse is quite large; hence it results in a large form factor in the circuit design. The pulse generation method is very sensitive to the reflections that may occur in the wave propagation paths; hence the operation of the circuit can be largely affected even by a small fabrication fault. The amplitudes of the pulses that can be generated by this method are limited to few hundreds of millivolts (mV) [1]. Hence it requires extensive amplification before transmitting through a wireless link. However, this method provides the basis for most of the modern UWB pulse generation techniques; that is the combining of a waveform and its delayed version in order to generate narrow pulses.

UWB pulse generators can be categorized into three major categories; namely (1) base band pulse generators, (2) up-conversion pulse generators and (3) waveform synthesis pulse generators. These three pulse generation techniques are further described in the following sections.

4.2.1 Base Band UWB Pulse Generators

In this approach, a base band pulse is generated initially in the form of a rectangular pulse [3–6]. The square base band pulse provides signal with a wide spectrum. However, initial base band pulse does not comply with the FCC spectrum requirements. Hence, a filtering stage is used in order to shape the pulse spectrum, such that it complies with the FCC spectral mask. This approach is shown in Fig. 4.1.

In base band pulse generators, the square pulse and its delayed version is passed through an XOR gate, forming an edge combining circuit. The narrow square pulses formed by the XOR output are then filtered using either a passive Band Pass Filter (BPF) [3, 5] or a Finite Impulse Response (FIR) based filter [7]. The square pulses that form the input to the XOR gate can be obtained either using the input data waveform itself [8, 9], through a flip-flop arrangement [5] or using a separate clock waveform [4].

An example pulse generator that uses a clock as the square wave signal source is depicted in Fig. 4.2 [10]. The use of an '*AND'* gate after the *'XOR'* gate creates IR-UWB pulses at every positive edge of the clock signal. The UWB pulses are then modulated with the data signal using another *'AND'* gate.

The base band pulse generation method provides advantages in terms of simplicity in design. It avoids the complexities of directly generating the UWB pulses that comply with the FCC spectrum requirements. A significant portion of the power spectrum of the square wave has to be filtered in order to bring the UWB pulse spectrum into the target frequency range. This results in significant power loss. The amplitude of the UWB pulse spectrum after the BPF stage is often lower than the FCC spectral mask. Thus, a power amplification stage may be needed after the BPF in order to use the maximum allowable spectral amplitude. The use of a power amplifier further increases power consumption of the UWB transmitter.

4.2.2 Up-Conversion-Based UWB Pulse Generators

The up-conversion method uses a mixer to up convert the frequency of the base band pulses into the target frequency range. Both rectangular [11] and triangular [12] pulses can be used as the base band pulse stream. Up-conversion of the pulses eliminates the requirement of a base band pulse with a wide spectrum, such as a square pulse in order to generate the final UWB pulse stream. Hence a triangular pulse stream is more suitable as the basis of the pulse generation. The power spectrum of the triangular pulses has suppressed side lobes, compared to that of the rectangular pulses. Hence the power loss that might occur by using a square wave pulse as the base band pulse can be reduced. However, it should be noted that although the triangular pulse generation techniques are easily achievable in CMOS IC based designs, the rectangular pulse based approach is the most convenient

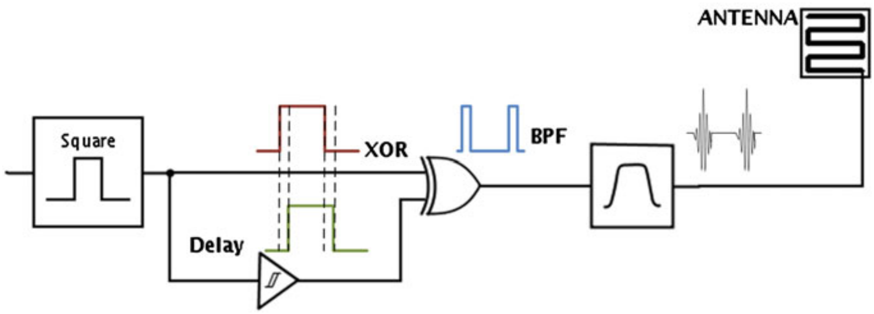

Fig. 4.1 Base band pulse generation approach

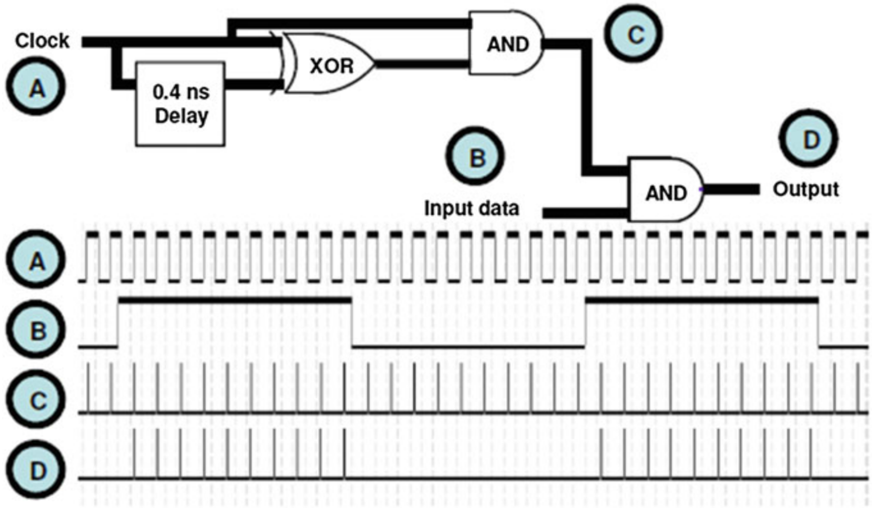

Fig. 4.2 An example pulse generation circuit [10], IEEE copyright

approach for the development of UWB pulse generators using off-the-shelf components. The up-conversion UWB pulse generation technique described in [12] is shown in Fig. 4.3.

In this method, the triangular pulse is generated using an integration circuit in combination with an inverter. The triangular pulse generator in fed with a Pulse Position Modulated (PPM) data waveform. The integration happens at the rising and falling edges of the data waveform. The amplitude of the baseband triangular pulse can be determined by the threshold of the integrator. The baseband triangular pulse is then up-converted into the higher frequencies using a mixer. The ring activation circuit activates the oscillator only when a pulse is present, hence it reduces the overall energy consumption of the circuit.

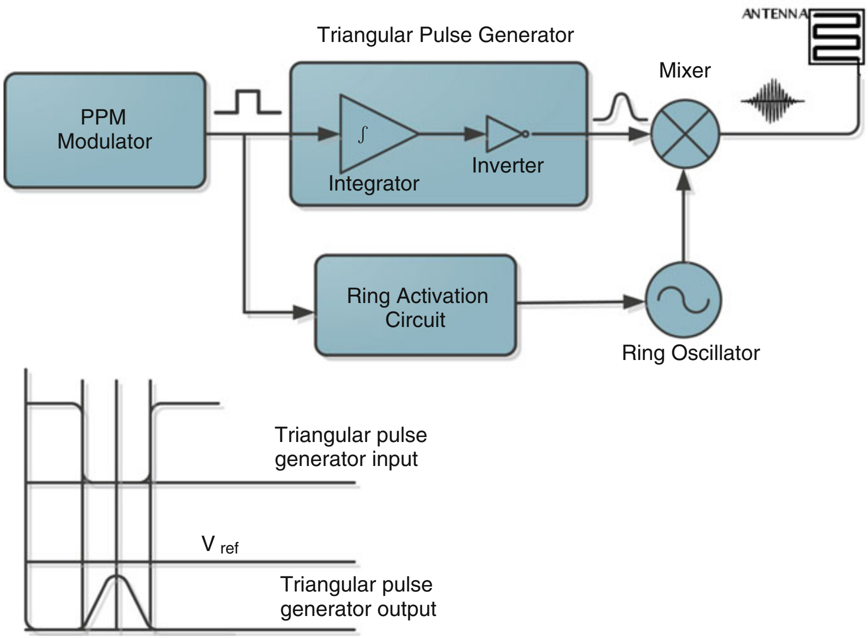

Fig. 4.3 Triangular pulse based up-conversion pulse generator

The use of an integrator for triangular pulse generation increases the power consumption of the circuit. A more efficient triangular pulse generation mechanism using logic gates is described in [13], where the triangular pulse is generated by edge combining the rising and falling edges of a square wave with an inverted version of itself.

The up-conversion pulse generation technique has the same advantages as the base band pulse generation technique. Additionally, the spectral shape of the final pulse can be determined in the base band domain in this method. Consequently, baseband pulse shaping techniques can be applied to this method rather than shaping the pulses at high frequencies. Hence, this approach minimizes the use of the power hungry RF components. However, this method also suffers from the relatively high power consumption in the mixer and the oscillator.

4.2.3 Waveform Synthesis (Pulse Shaping) Techniques for UWB Pulse Generators

In some UWB pulse generators, UWB pulses are directly synthesized in the targeted frequency range using pulse-shaping techniques. Unlike base band pulse generators, this type of UWB pulse generators do not use a base band pulse stream to filter out the signals with spectral portion at the target frequency range. It uses

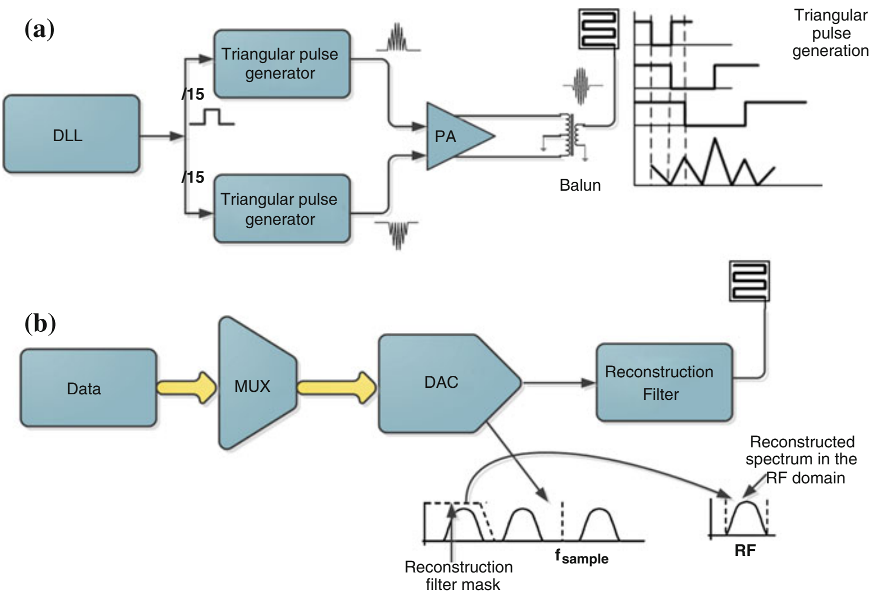

Fig. 4.4 Waveform synthesis UWB pulse generators **a** triangular pulse synthesis **b** DAC based pulse synthesis

waveform synthesis techniques to directly synthesize UWB pulses such that they directly fall within the target frequency range without using any filtering techniques. Direct synthesis of the UWB pulses can be realized using several methods. The methods shown in [14, 15] generate triangular pulses in the RF domain. A fully digital implementation of a triangular UWB pulse generator is described in [14]. In this method, the triangular pulses are generated by combining the edges of several square pulses created using a Delay Locked Loop (DLL) (Fig. 4.4a). The pulse shape can be digitally controlled by varying the delay of the original square pulses; hence, it is preferred over the analog pulse generation techniques for low power applications. Power amplification is applied for the negative and positive triangular pulses separately. Finally, the pulses are combined using a balun. This method provides more controllability over the pulse generation at the cost of increased hardware complexity.

A less complex, logic gate based triangular pulse generation technique is presented in [15]. In this method, the triangular pulses generated using a combination of XOR gates are used to periodically switch a voltage controlled ring oscillator. In this manner it is possible to generate the triangular UWB pulses in the RF domain. Since the oscillator operates only during the presence of a pulse, this method reduces the power wastage due to the continuous operation of local oscillators in the other methods.

A Digital to Analog Converter (DAC) based direct UWB pulse synthesis approach is demonstrated in [16] (Fig. 4.4b). This technique uses a high speed DAC in order to synthesize accurate UWB pulse in the RF domain. This method overlooks the precision in pulse generation, hence the achievable controllability in the pulse spectrum over the hardware complexity. The main drawback of this approach is that the DAC has to operate at very high sampling rates (in the order of 10 Gsps) in order to generate the UWB pulses. This is not only challenging for the implementation of the DAC, but also the input data stream has to operate at very high rates; hence it demands the use of high speed logic circuits. In general, the waveform synthesis UWB pulse generation method is suitable for on-chip implementations using advanced technologies such as CMOS due to the requirement of the high precision in circuit implementation.

4.3 UWB Receiver Design Techniques

Due to the short pulse width and low power of the signal, front-end circuitry for the UWB receiver is complex in design and has high power consumption. An Analog to Digital Converter (ADC) in a UWB receiver requires a large input bandwidth and a high sampling rate. For example ADC12D1800 [17] by National Semiconductors has 3.5 Giga samples per second sampling rate and an input bandwidth of 1.75 GHz, but it consumes 4.4 W of power which is not suitable for battery powered UWB sensor design. Although the ADC has been brought close to the antenna with the evolution of the front-end circuitry for narrow band systems, it is not considered as a suitable technique for UWB systems. The fully digital implementations of the UWB receivers require precise synchronization of nanosecond scale narrow UWB pulses and resolving numerous multipath components of the received UWB signals [18].

UWB receivers are of two types: non-coherent receivers and coherent receivers. These two receiver architectures are discussed in following sections.

4.3.1 Non-Coherent UWB Receivers

Non-coherent UWB receivers can be further sub-divided into two categories: Energy Detection (ED) receivers and Autocorrelation (AcR) receivers. ED UWB receiver architectures are discussed in [19, 20]. In this receiver type, a squaring device is used to correlate the received UWB signal with itself. This can be achieved by operating a MOSFET in the saturation region. Block diagram of the receiver described in [20] is shown in Fig. 4.5. The ED UWB receivers do not require channel estimation; hence hardware complexity is greatly reduced. This leads to superior performance in terms of power consumption. However the Signal-to-Noise Ratio (SNR) of this type of receivers is inferior to other types of UWB receivers mainly due to use of the noisy received signal as the template signal. Also, the receiver performance degrades rapidly in an environment with a large number of interferers.

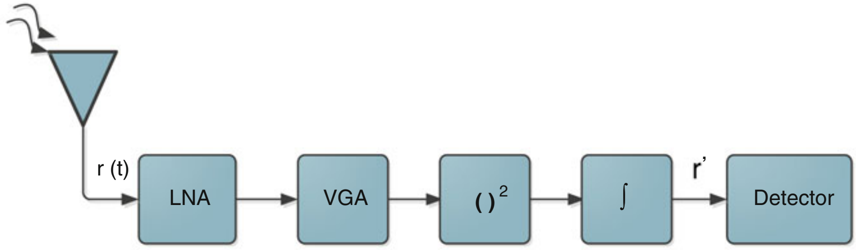

Fig. 4.5 An energy detection non-coherent UWB receiver

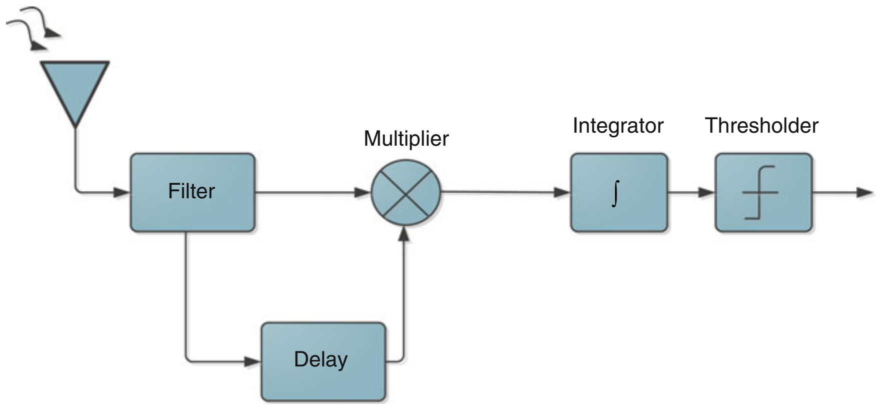

Fig. 4.6 An autocorrelation non-coherent UWB receiver

AcR receivers use a delay path and a multiplier circuit instead of the squarer circuit in the energy detection receiver. The operation of AcR receivers is based on the use of a reference pulse that is transmitted by the transmitter in order to correlate with the data modulated pulses that follow the reference pulse. The reference pulse that is transmitted prior to every data modulated pulse is delayed using a delay line, and is used as the signal template for the data reception that follows. The channel information embedded in the reference pulse improves the performance of the receiver by reducing the Inter Symbol Interference (ISI). Basic diagram of an AcR receiver is shown in Fig. 4.6. Performance of AcR receivers is discussed in [21, 22]. The main drawback of an AcR receiver is the requirement of a precise delay line. It also suffers from performance deterioration due to the use of a noisy template.

The BER performance of both the ED and the AcR receivers depend on the integration window time, which determines the amount of signal energy gathered during the integration period [18]. Further, it has shown in [18] that the ED receiver outperforms the AcR receiver in terms of BER for OOK and Binary Pulse Position Modulation (BPPM) schemes. Results in [23] demonstrates that the ED receiver is more power efficient than the AcR receiver.

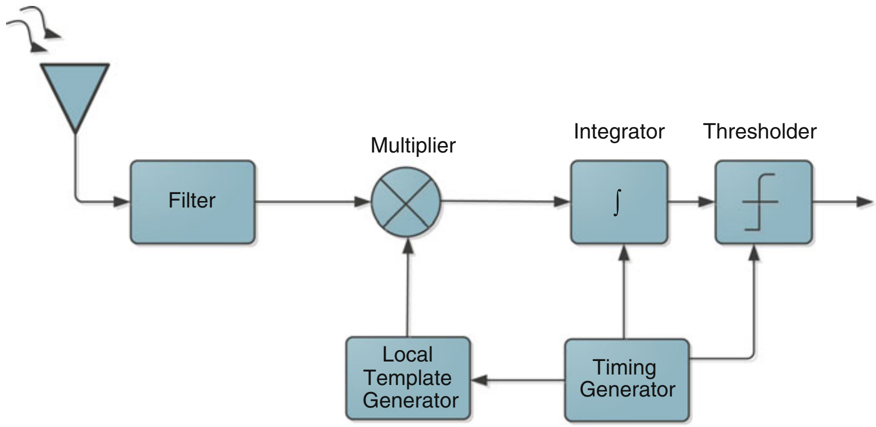

Fig. 4.7 A coherent UWB receiver

4.3.2 Coherent UWB Receivers

In a coherent receiver, correlation is performed between the received waveform and a locally generated template of the waveform. It requires having a good estimate of the channel, and a template generation mechanism, which makes it complex in design and high power consuming. The development of an optimum coherent receiver is demonstrated in [24]. Figure 4.7 depicts a basic block diagram of the optimum coherent receiver architecture. The template generated at the local template generator of the optimum coherent receiver is closely matched to the transmitted signal. It also has to perform channel estimation in order to compensate for the presence of multipath components. This results in increased design complexity and high power consumption.

Coherent rake receivers use energy of precise multipath components of the UWB signal in order to reconstruct the original waveform [25]. This type of coherent receivers requires large number of rake fingers due to the high temporal resolution of the UWB signals. Performance of both types of coherent receivers deteriorates with timing jitters and synchronization errors [26]. Performance of coherent receivers is compared with that of a non-coherent receiver in [27, 28], which show that better accuracy can be obtained in coherent receivers at the cost of high circuit complexity and high power consumption. It has been shown in [28] that a non- coherent receiver will perform better than a coherent receiver for timing jitter values above 18 ps.

4.4 UWB Sensor Node Designs

While many publications present the implementation of UWB transmitters in Integrated Circuits (IC), only few publications present the full implementation of UWB based sensor platforms that should other peripheral electronics, such as

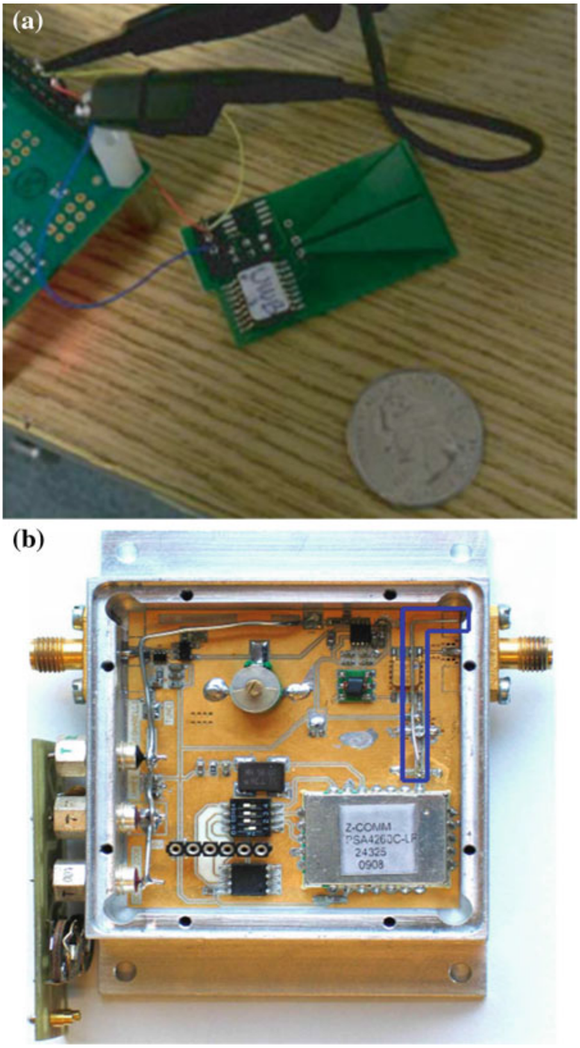

Fig. 4.8 UWB sensor node designs **a** [29] **b** [30], IEEE copyright

micro-controllers, sensor front-end circuits, receiver back-end processing units and matching circuits. This section presents some of the full implementations of UWB based sensor nodes that can be found in literature.

An UWB sensor node built based on a UWB pulse generator IC is presented in [29] (Fig. 4.8a). In this design, switched voltage control ring oscillator approach is used in order to generate the UWB pulses. The data is fed into the circuit using a Field Programmable Gate Array (FPGA) and is modulated using the pulse stream generated by the aforementioned pulse generation technique. This work also presents the implementation of a UWB antenna on the same Printed Circuit Board

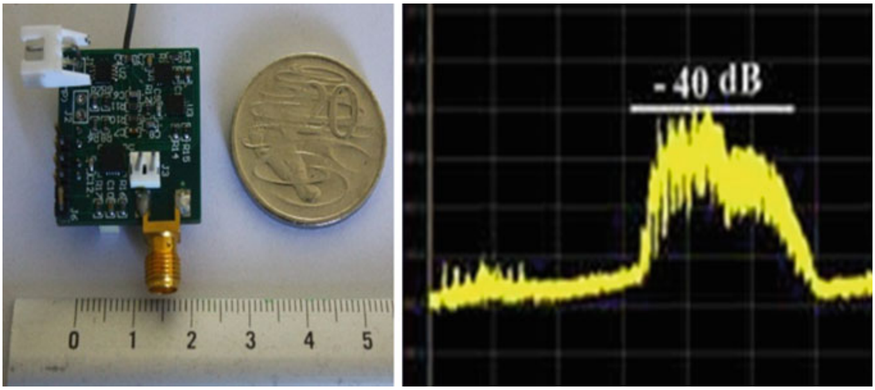

Fig. 4.9 Amplifier based UWB sensor node design and transmit spectrum

(PCB). This sensor node is not fully integrated for independent operation as the data and the control signals have to be generated using an external FPGA.

A UWB transmitter developed using off-the-shelf components is presented in [30]. In this method, narrow square pulses are generated in the base band domain using a series of comparators. The RF pulses are generated by mixing these narrow pulses with a high frequency signal generated using a phase locked loop. The power consumption of this circuit is 660 mW; hence it is not suitable for power stringent UWB applications.

A transmit-only UWB sensor node design is presented in [31, 32] (Fig. 4.9). Its main operational blocks are depicted in Fig. 4.10. The sensor nodes are assembled on a four layer PCB with dimensions of 27 mm (L) $\times$ 25 mm (W) $\times$ 1.5 mm (H), which is sufficiently compact for the use in a wearable WBAN node. This sensor node is designed using an amplifier based hardware architecture. In this design, the narrow base band pulses are filtered using a BPF with a pass-band of 3.5–4.5 GHz. The UWB pulses are then amplified using a wideband low noise amplifier (LNA) to meet the -41.3 dBm transmission power level. This amplifier has been included to guarantee that the amplitudes of the UWB pulses are sufficient to provide a targeted coverage by a WBAN application.

The power spectrum of the UWB pulses generated using this sensor node is shown in Fig. 4.11. This power spectrum consists of several frequency lobes spread throughout the UWB bandwidth. The amplitudes of these frequency lobes decrease towards the upper part of the UWB spectrum. The UWB sensor node is designed to transmit UWB signals in the band of 3.5–4.5 GHz. As shown in Fig. 4.11a, the amplitude of the frequency lobe within the 3.5–4.5 GHz band is well below the maximum allowable power level by the FCC (-41.3 dBm/MHz). This sensor node design employs two amplifier stages in order to boost the power level of the transmitted UWB signal within the band of 3.5–4.5 GHz (as marked in Fig. 4.11) while containing the power level within the FCC spectral mask.

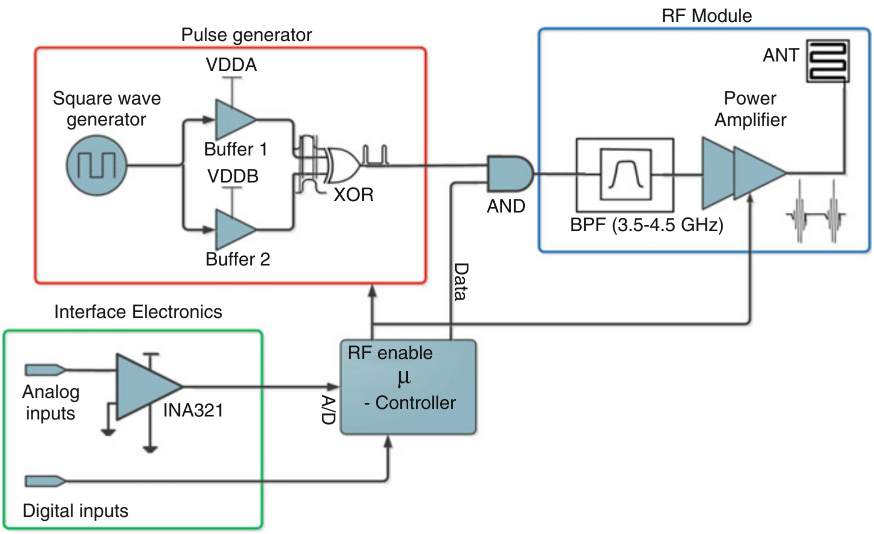

Fig. 4.10 Amplifier based UWB sensor node design

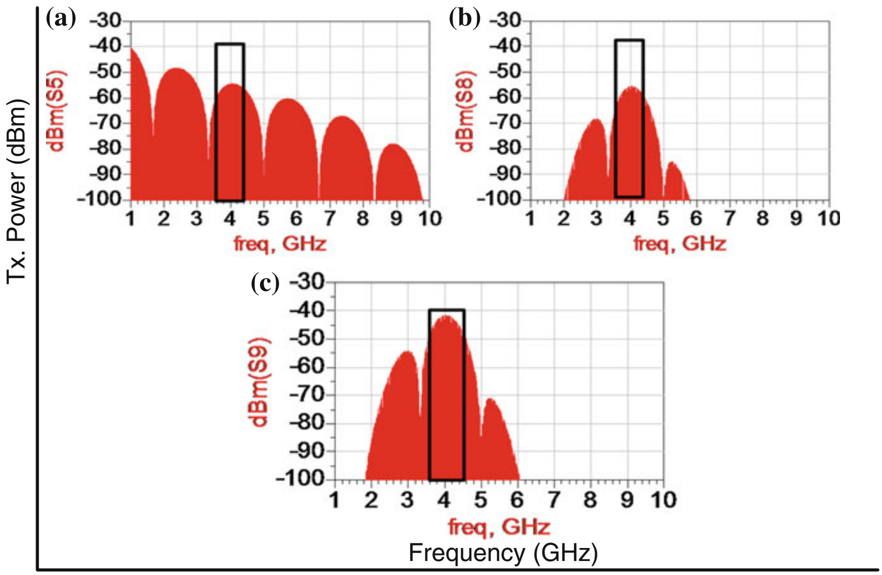

Fig. 4.11 Frequency spectrum of amplifier based sensor node at **a** pulse generator output **b** band pass filter (3.5–4.5 GHz) output, and **c** amplifier output

4.5 Conclusion

This chapter gives a brief introduction for some of the commonly used transceiver architectures used in UWB hardware implementations. Three types of pulse generators used in UWB transmitter developments are discussed, namely: base band pulse generators, up-conversion based pulse generators and waveform synthesis pulse generators. Among these three pulse generation methods, up-conversion based pulse generation method provides significant advantages in terms of low power consumption and simple design. This method can be considered as a suitable design technique for UWB transmitters. Waveform synthesis pulse generators generate pulses directly in the intended frequency range of an UWB application without using an intermediate base band stage. They are more complex in design compared to the up-conversion method. This type of pulse generators can be considered as a suitable design technique for IC based power efficient UWB hardware designs.

UWB receivers are inherently complex in design compared to UWB transmitters. This is mainly because of the fact that UWB receivers have to receive low power narrow UWB signals and have to perform functions, such as precise synchronization of narrow UWB pulses. There are two main realizations of UWB receivers: coherent receivers and non-coherent receivers. Non-coherent UWB receivers are better suited for WBAN applications mainly due to less complex hardware design and low power consumption. Out of the non-coherent UWB receivers, ED receivers are preferable over the AcR receivers, especially for short-range applications where a strong Line-Of-Sight (LOS) is present. This is mainly due to the fact that AcR receivers require the synthesis of precise delay lines, which leads way to complex hardware synthesis.

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