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Ultra-Wideband RF Transceiver

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1. Introduction

Ultra-wideband (UWB) technology has developed rapidly over the past several years due to its high date rate with small current consumption in short range communication. According to Shannon-Hartley theorem, the maximum rate of clean (or arbitrarily low bit error rate) date through an AWGN (Additive white Gaussian Noise) channel, is limited to

$$C = BW \cdot \log_2 \left(1 + SNR\right) \tag{1}$$

Where, C is the channel capacity, BW is the bandwidth, SNR is the ratio of average received signal power to the noise spectral density. It can be seen from (1), channel capacity increases linearly with bandwidth but only logarithmically with SNR which means capacity increases as a function of BW faster than as a function of SNR and with a wide bandwidth, high data rate can be achieved with a low transmitted power. Its main applications include imaging systems, vehicular radar systems and communications and measurement systems. Ever since, the FCC released unlicensed spectrum of 3.1-10.6 GHz for UWB application in 2002, UWB has received significant interest from both industry and academia. Mutli-Band OFDM (MB-OFDM) and Direct-Sequence UWB (DS-UWB) are two existing competing proposals for UWB; each gained multiple supports from industry. The MB-OFMD divides the 3 ~ 10 GHz UWB spectrum into fourteen sub-bands which has a 528 MHz bandwidth. Due to incompatible of these two proposals, it experiences huge difficulties in commercialization of UWB technology. On the other hand, Impulse Radio UWB (IR-UWB) has become a hot research area in academia due to its low complexity and low power.

2. UWB modulation

As UWB pulse itself does not contain information, we must add digital information to the analog pulse through modulation. The MB-OFDM systems are dealing with

continuous ultra-wideband modulated signals while DS-UWB systems are transmitting discrete short pulses which cover ultra-wide bandwidth. On the other hand, IR-UWB is a carrier-less pulse-based system which means IR-UWB and DS-UWB are the two different categorizes of pulse based UWB. Pulse modulation scheme includes OOK (On Off Keying), BPSK (Binary Phase Shift Keying) and PPM (Pulse Position Modulation). OOK modulation is performed by generating transmitted pulses only while transmitting '1' symbols. BPSK modulation generates 180° phase-shifted pulses while transmitting baseband symbols '1' and '0'. PPM modulation is performed by generating pulses where each pulse is delayed or sent in advance of a regular time scale. Thus a binary communication system can be established with a forward and backward shift in time. By specifying specific time delays for each pulse, an M-ary system can be created. BPSK has an advantage over other modulation types due to an inherent 3 dB increase in separation between constellation points (Wentzloff & Chandrakasan, 2006); however, BPSK modulation is not suitable for some receiver architectures, e.g., noncoherent receivers.

3. UWB transceivers

Both MB-OFDM (Ranjan & Larson, 2006; Zheng H et al., 2007; Bergervoet et al., 2007; Beek et al., 2008) and DS-UWB (Zheng Y. et al., 2007, 2008) are carrier-modulated systems, where a mixer is used to up/down convert the radio frequency (RF) signal, therefore it requires local oscillator (LO) synthesis. On the other hand, IR-UWB (Yang, C. et al., 2005 ; Xia L. et al., 2011) is a carrier-less pulse-based system, therefore, we can eliminate the fast hopping LO synthesis, thus reducing the complexity and power consumption of the entire radio. Furthermore, since the signal of a pulse-based UWB system is duty-cycled, the circuits can be shut down between pulses intervals which would lead to an even lower power design.

There are a number of different fabrication options for UWB transceivers; CMOS is mainly compelling due to its low cost, low power consumption and single chip transceiver architecture with few external components. Poor passive components and lower operating voltages associated with process scaling pose significant problems for the radio architect and designer. Moreover, the design of UWB transceivers faces the following issues such as - 1) broadband circuits and matching; 2) the low-noise amplifier (LNA) with reasonable noise figure (NF) and impedance matching 3) broadband transmit/receive switch. Narrowband interference imposes some extra issues- the linearity and dynamic range. Even though some important issues that impact the receiver design are given above, there are many other factors that affect the receiver design and choice. For example, the modulation that is used at the transmitter impacts the receiver design. If the transceiver complexity and cost are the primary concerns, a scheme that enables noncoherent demodulation (OOK, positive PAM, PPM, and M-ary PPM) can be considered. On the other hand, some other modulations like BPSK, M-ary PAM, and QAM have the potential to provide better performance and require coherent demodulation since the information is embedded in the polarities of the pulses.

3.1. UWB transmitter/Pulse generator

In principle, all the pulses with the spectra (≥ 500 MHz) falling into the UWB band can be used as signals. However, for practical purposes, the pulses which are simple to generate, controlled, and have low power-consumption (no direct component), are selected to generate UWB signals. The proper selection of the source pulse can maximize the radiated power within the UWB band and meet the required emission limits without filters before the transmitting antennas while minimizing anticipated inter-symbol (and in the case of DS-UWB, inter-chip) interference and providing spectral flexibility as a method to coexist with other radio systems.

In the transmitter, the binary information stream from devices such as PC, PDA or DVD player is passed to the front end of the transmitter and mapped from bits to symbols if higher order modulation schemes are to be used. Each symbol representing multiple bits is then mapped to analog pulse shape which is generated by pulse generator. The mapping of information into waveforms is referred to data mapping or modulation. The generated pulse then can be optionally amplified before being passed to transmitting antenna. Typical IR-UWB use transition generators with edge rates designed to occupy 3 GHz of bandwidth or more while other systems use various forms of gated frequency generators, where the edge rates are selected to spread the energy around the fundamental frequency of the generator.

3.2. UWB receiver

It is necessary to have an optimal receiving system same as generating signal with the desired spectral characteristics. The optimal receiving technique often used in UWB is a correlation receiver. The correlator in the receiver multiplies the received signal with the template waveform. It is critical to note that the mean value of the correlator is zero. Thus, for in-band noise signals received by a UWB radio, the correlator's output has an average value of zero. Moreover, the standard deviation or rms of the correlator output is related to the power of those in-band noise signals. The level of hardware implementation and computational complexity plays an important role in determining which modulation to be used in what application.

The receiver sensitivity is generally defined by the signal level required to gain the given signal-to-noise (S/N) ratio. This means sensitivity is increased when there is less noise. The following formula shows the factors used to define receiver sensitivity.

$$S \ (dBm) = -174 + NF + 10 \log B + 10 \log(S/N) \tag{2}$$

Where, S (dBm) is the receiver sensitivity, NF is the noise figure, B is the bandwidth and S/N is the signal to noise ratio.

If communication is established by QPSK with 8 dB of S/N ratio and 6 dB of total circuit NF, receiver sensitivity with MBOFDM receiver will become –73dBm, when the bandwidth, B= 528 MHz for the data rate 480 Mb/s, To raise the data rate from 54 to 480 Mb/s, the channel

bandwidth B need to increase from 20 to 178 MHz. MB-OFDM derives the receiver sensitivity requirements ranging from -80.8 dBm (for 54 Mb/s) to -73 dBm (for 480 Mb/s) at different data rates. If the required SNR is 2.4 dB, the receiver noise figure is 11.7 dB and the channel bandwidth is 1.32 GHz, the receiver sensitivity with a DS-UWB receiver will become –76.5 dBm at 220 Mb/s.

4. RF transceiver for IR-UWB

The transmitter for IR-UWB integrates amplitude and spectrum tunability, thereby providing adaptable spectral characteristics for different data rate transmission. The receiver employs noncoherent architecture because of its low complexity and low power. A 3-5 GHz fully integrated IR-UWB transceiver is presented as shown in Fig. 1 (Xia et al., 2011). IR-UWB transceiver is implemented in a 0.13 μm 1P8M CMOS technology. The transceiver die microphotograph is shown in Fig. 2. The die area is 2 mm×2 mm. The chip is bonded to the 4-layer FR-4 PCB with chip-on-board (COB) assembly. With a supply voltage of 1.2 V, the power consumption of the transmitter is only 1.2 mW and 2.2 mW when transmitting 50 Mb/s and 100 Mb/s baseband signals, respectively; the power consumption of the receiver is 13.2 mW.
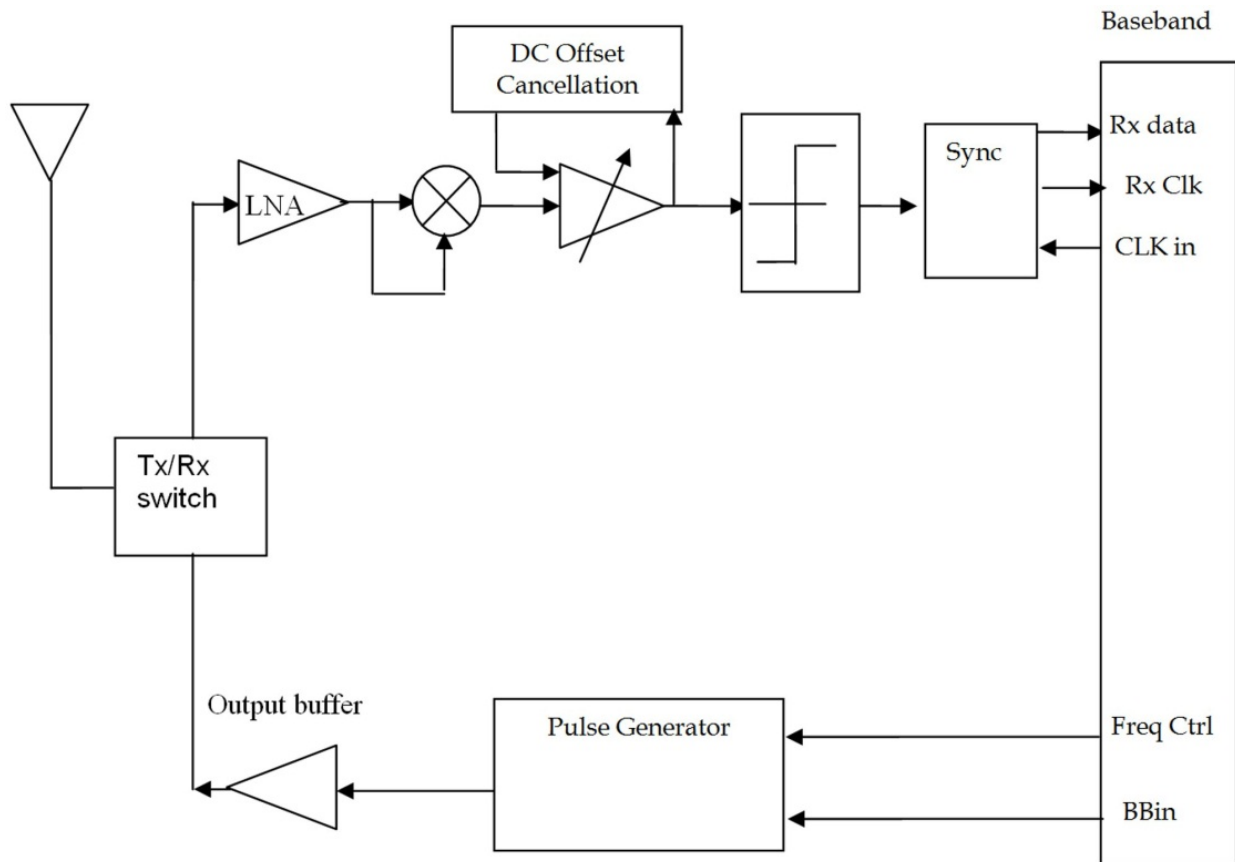

Figure 1. The proposed IR-UWB transceiver system architecture with OOK modulation
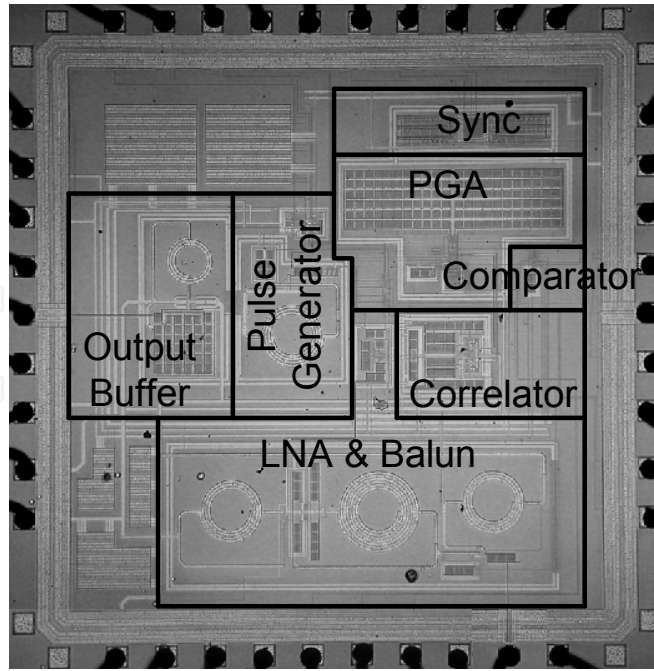
Figure 2. Microphotograph of IR-UWB transceiver

In fact, most companies are diving head-on into DS-CDMA and MB-OFDM to form the foundation for most of the coming UWB products though the impulse approach is the hot research area in academia.

5. DS-UWB scheme and RF transceiver

Direct-sequence spread-spectrum (DSSS) technique is a powerful multiple access (MA) technique that could be combined with UWB modulation to provide robustness against interference. In DS-UWB, the data to be transmitted is modulated using bipolar modulation, based upon a certain spreading code. Modulation is either phase-shift keying (PSK) or PPM. DS-UWB transmitters are super simple and use very low power, but the receiver and its complex correlation recovery circuits are somewhat more of a challenge. DS-UWB has many attractive properties, including low peak-to-average power ratio and robustness to multiple access interference (MAI) [Win et al., 1997].

The basic transmitted CDMA waveform of user k is given by

$$x_k(t) = \sum_{j=0}^{N-1} C_j^k w\left(t - jT_c\right) \tag{3}$$

Where, $w(t)$ represents the transmitted monocycle and C_j^k denotes jth spreading chip of the pseudo-random noise (PN) Sequence. N is the number of pulses of the PN sequences to be used for each user.

The transmission signal format is shown in Fig. 3. The encoded data of each user are considered as a data symbol, which is multiplied by the transmitted CDMA code.
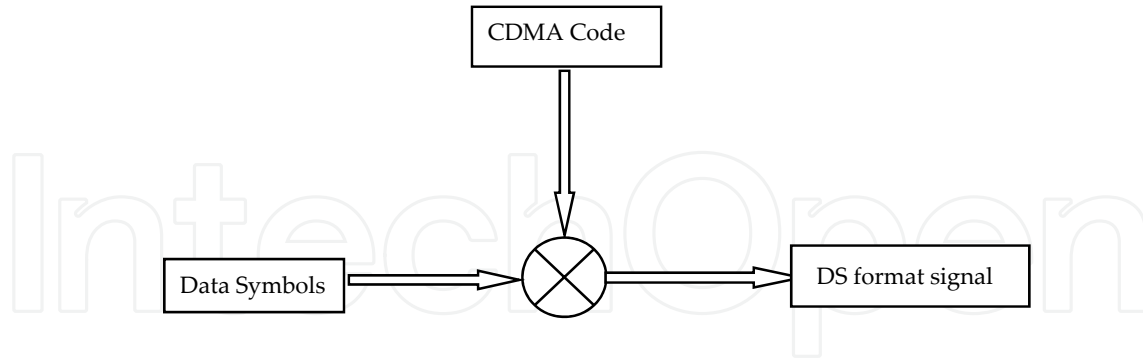
Figure 3. Transmission signal format

Let, T_f be the symbol period and T_c be the chip period such that $T_f = NT_c$. Hence, a typical DS format of the *k*th impulse radio transmitter output signal is given by

$$S_k(t) = \sqrt{p_k} \sum_m d_m^k \, x_k(t - mT_f) \tag{4}$$

Where d_m^k represents the data symbols and p_k is the transmitted power corresponding to the *k*th user. It is important to note that even an ideal channel and antenna system modify the shape of the transmitted monocycle *w(t)* to *w$_{rec}$(t)* at the output of the receiving antenna, where *w$_{rec}$(t)* is the derivatives of a Gaussian function.

As indicated in [Ge et al., 2002, Wu et al., 2002, Wang et al., 2007], the DS-UWB system performance is severely downgraded by inter-symbol and multiple access interferences. Hence, researches on reducing effects of inter-symbol interference (ISI) and MAI is of great importance in designing of the transceiver for DS-UWB [Nassar et al. 2003]. The transceiver architecture of DS-UWB is shown in Fig.2 and the building blocks have bee presented in the following subsections.

5.1. Low noise amplifier

The primary factors in choosing a low noise amplifier (LNA) scheme are noise figure, dynamic range, linearity and power consumption. LNA is not the first block of a receiver circuit. It is followed by a band pass filter, a switch, or a duplexer that has to be implemented as a first block of the receiver chain in front of Low noise amplifier (LNA). As the band-pass filter is constructed with LC-tank in the first stage mixer to perform filtering of out-of-band interference and this block has signal loss characteristics instead of signal amplification, LNA requires providing a reasonable noise figure (NF) and impedance matching. By using a darlington topology a high gain can be achieved over the entire operating band. The design of a UWB LNA is more challenging than a traditional narrow-band LNA. Detailed design and consideration of the LNA can be found in [Hu et al., 2010; Lee H-J, 2006].
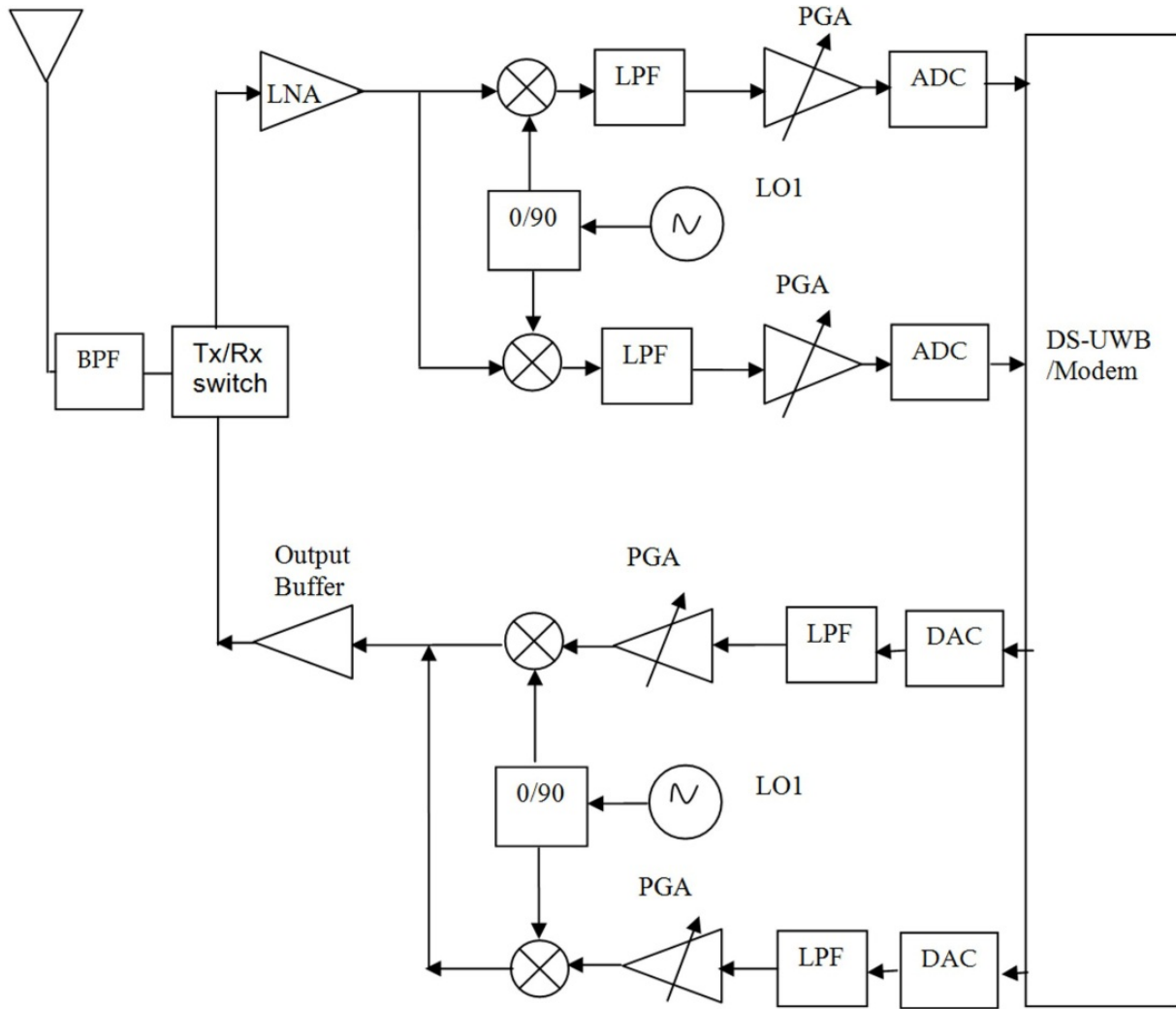
Figure 4. DS-UWB transceiver

5.2. Mixer

A combined mixer is proposed for both RF down-conversion in RX and for the RF up-conversion in the TX. In the receiver, it needs to synchronize the received pulse with local controlling signals to down-converted first. For superheterodyne transceivers, it is further down converted to baseband signal by a quadrature mixer. Because of the two stage frequency translation, local oscillator leakage does not have a significant impact on the receiver. In case of direct conversion transceiver, the RF signal is directly down-converted to baseband signal without any intermediate frequency. Therefore, the cost and size of the overall transceiver are reduced. The double-balanced Gilbert-type mixer topology has been widely used due to its low oscillator leakage and low even-order distortion products at the output.

5.3. Bandpass filter

The UWB filters are required to have a specified a small bandpass filter (BPF) with a notched band in the UWB passband (for DS- UWB) in order to avoid being interfered by the

5–6 GHz for IEEE 802.11a wireless local area networks (WLANs). To avoid the frequency use of WLAN radio signals, the direct sequence ultra-wideband (DS–UWB) specifications for wireless personal area networks (WPANs) need further to divide into a low band of 3.1–4.9 GHz and a high band of 6.2–9.7 GHz [IEEE.15 Working Group].

5.4. Variable Gain Amplifier

Variable gain amplifier (VGA) is an essential block at the front end of ultra-wideband transceiver to maximize the dynamic range of the receivers. VGAs are also used in the transmitter part of ultra-wideband transceivers to control the transmission signal power. The VGA is typically implanted in an automatic gain control amplifier (AGC) loops to provide constant output signal regardless the variations in the input signal. The variable gain amplifier suppresses even harmonics, rejects common-mode noises and provides good linearity and wideband performance regardless of the control voltage.

6. Multiband OFDM (MB-OFDM) scheme and transceiver architecture

According to (Batra et al., 2003, 2004a, 2004b), Multiband OFDM (MB-OFDM) scheme divides the available band into 14 sub-bands of 528 MHz each, as illustrated in Fig. 5. Each subband contains 128 subcarriers of which 10 are used for guard tones and can be used for various purposes, 12 are dedicated to the pilot signals and 100 are for information. It can be seen from the figure, each band group being made from three consecutive sub-bands, except for the fifth one which encompasses only the last two sub-bands. A WiMedia compatible device uses only one out of these six defined channels. Initially, most of the studies done in the literature have been performed on the first band group from 3.1 to 4.8 GHz.

The MB-OFDM system can transmit information at different data rates varying from 53.3 to 480 Mbps, listed in Table 1. These data rates are obtained through the use of different convolutional coding rates, frequency-domain spreading (FDS) and time-domain spreading (TDS) techniques. FDS consists in transmitting each complex symbol and its conjugate symmetric within the same OFDM symbol. It is used for the modes with data rates of 53.3 and 80 Mbps. With the TDS, the same information is transmitted during two consecutive OFDM symbols using a time-spreading factor of 2. It is applied to the modes with data rates between 53.3 and 200 Mbps.

In MB-OFDM, quadrature phase-shift keying (QPSK) and dual carrier modulation (DCM) are used for data modulation. For data rates lower than 320 Mbps, the constellation applied to the different subcarriers using quadrature phase-shift keying (QPSK) and for data rates of 320 Mbps and higher, the binary data is mapped onto two different 16-point constellations using a dual-carrier modulation (DCM) technique.

As illustrated the MB-OFDM transmitter in Fig. 6, the first LO1 signal down-converts RF signals to a fixed IF which is further down converted to another IF by LO2. As a unique feature of MB-OFDM transceiver, a single RF mixer is proposed for both RF to IF down conversion in the receiver and IF to RF up conversion in the transmitter.
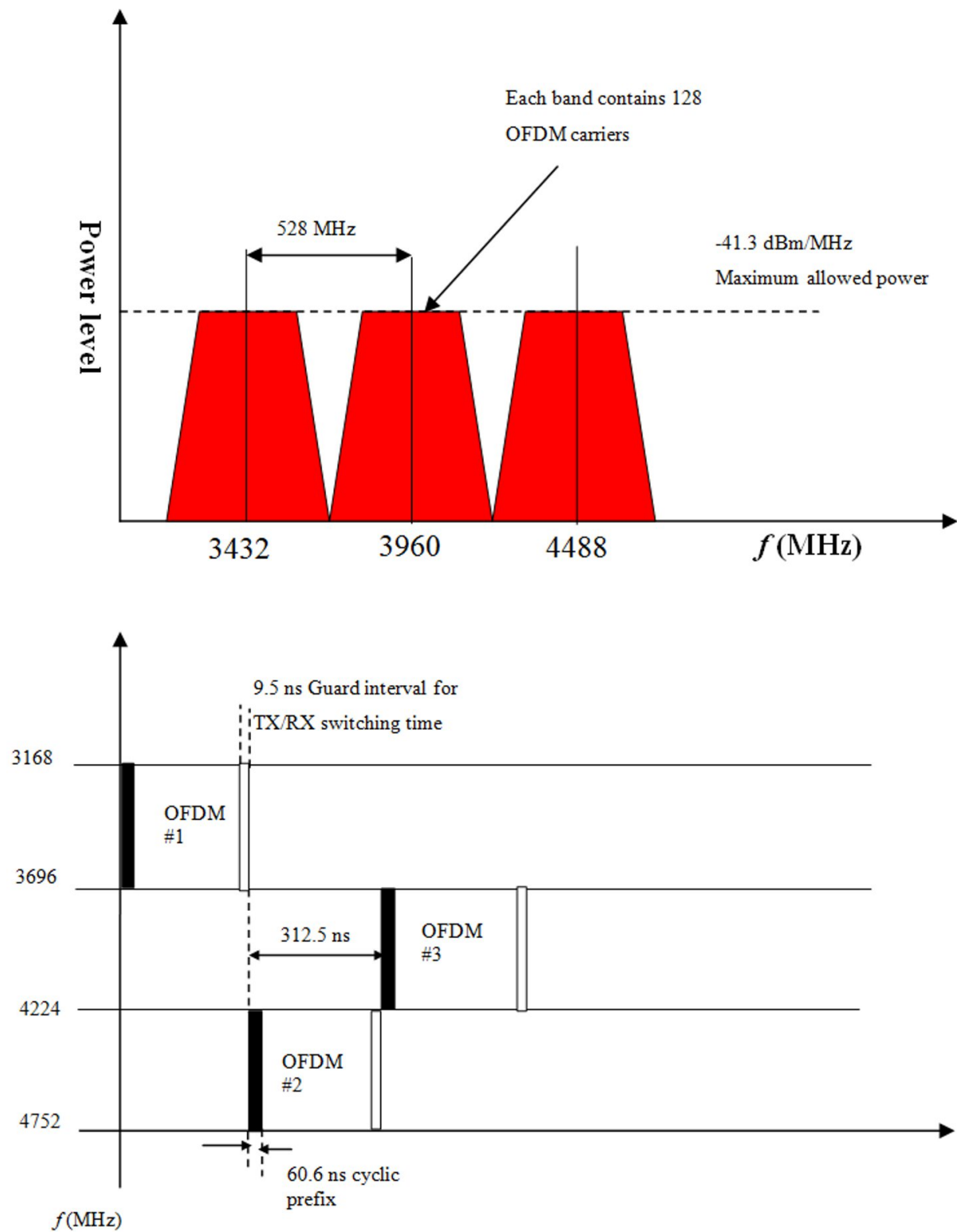
Figure 5. MB-OFDM system

Info. Data Rate (Mbps)	Modulation/ Constellation	FFT Size	Coding Rate (K=7)	Spreading rate
53.3	OFDM/QPSK	128	1/3	4
55	OFDM/QPSK	128	11/32	4
80	OFDM/QPSK	128	1/2	4
106.7	OFDM/QPSK	128	1/3	2
110	OFDM/QPSK	128	11/32	2
160	OFDM/QPSK	128	1/2	2
200	OFDM/QPSK	128	5/8	2
320	OFDM/QPSK	128	1/2	1
400	OFDM/QPSK	128	5/8	1
480	OFDM/QPSK	128	3/4	1

Data Rate =640Mbps*Coding Rate/Spreading
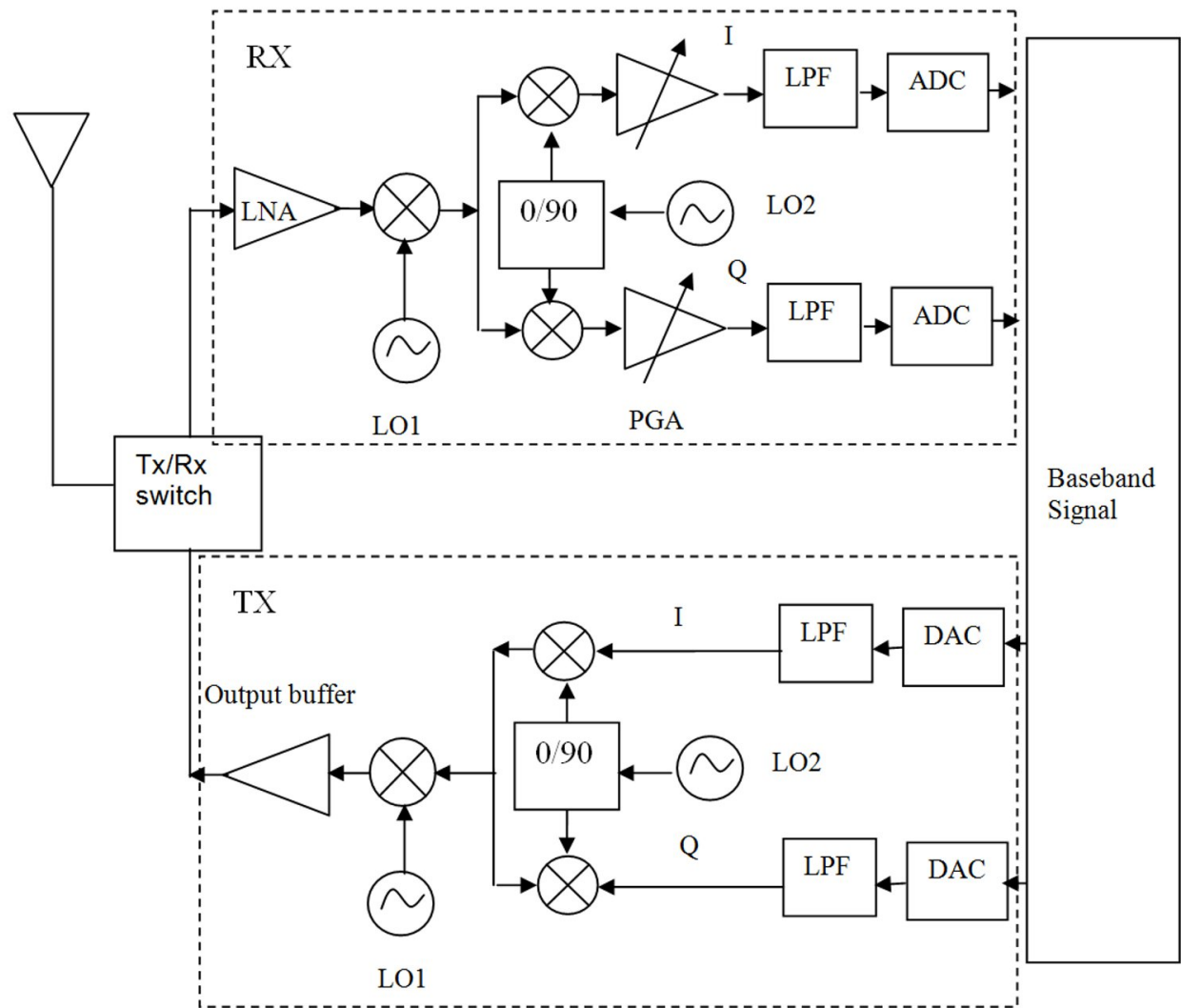
Table 1. Data rate dependent parameters [26]

Figure 6. MB-OFDM Transceiver

7. UWB antennas

An UWB communication system requires transmitter and receiver with a wideband antenna. Antennas are the fundamental component of a communication system, both at the receiver and at the transmitter, subject to performance requirements while at the same time supporting demand constraints to incorporate it in terminals or network access points. The contradiction between requirements and constraints make the selection or the design of an antenna something difficult in the ultra-wideband (UWB) case as the large bandwidth places additional needs in comparison to narrowband radio. The second problem for the antenna designer is the lack of tools to evaluate the performance of an antenna embedded in a radio system, apart from tools intended to determine the antenna input impedance, gain, efficiency, and its radiation patterns. These tools are obviously quite important in order to describe where the direction of the radiation would go or would be received, and what signal power can be lost due to antenna losses, but nothing about the "matching" between the antenna and the channel. It is well known that matched filtering is a necessary requirement for optimal signal reception, therefore since both antennas and channels are filters that are involved in the transfer function between the signal to be transmitted and the signal at the receiver output. This means, we should analyze antenna performance and channel properties in a correlated manner, if optimization of the radio link performance is a goal to reach.

As Antennas are considered to be the largest components of integrated wireless systems; antenna miniaturization is necessary to achieve an optimal design. The printed antennas present good solution because of providing several advantages compared to the conventional microwave antennas. The main advantages are: lightweight, small volume, low-profile, planar configuration, compact, can be made conformal to the host surface, easy integrated with printed-circuit technology and with other MICs on the same substrate, low cost, allow both linear polarization and circular polarisation. Monopole disc antennas, with circular, elliptical and trapezoidal shapes, have simpler two-dimensional geometries and are easier to fabricate compared to the traditional UWB monopole antennas with three-dimensional geometries such as spheroidal, conical and teardrop antennas. These disc monopole antennas can be designed to cover existing and upcoming UWB communication applications, (Honda et al., 1992) & (Hammoud & Colomel, 1993).

In the last few years, circular monopole antennas have been studied extensively for UWB communications systems because of some appealing features (easy fabrication, feedgap optimization alone gives wide impedance matching and omnidirectional radiation patterns). One of the strongest competitors in terms of good impedance bandwidth, radiation efficiencies, and omnidirectional radiation patterns are the circular disc monopole (CDM) and elliptical antennas (Abbosh & Bialkowski, 2008; Allen et al., 2007; Antonino et al., 2003, Liang et al., 2004; Powell, 2004; schartz, 2005; Srifi et al., 2009). There is great demand for UWB antennas that offer miniaturized planar structure, so the vertical disc monopole is still not suitable for integration with a PCB. This drawback limits its practical application. For this reason, a printed structure of the UWB disc monopole is well desired, which consist on

printed radiator disc on substrate. Printed CDM antennas can be fed simple microstrip line, coplanar waveguide (CPW), or slotted structures.
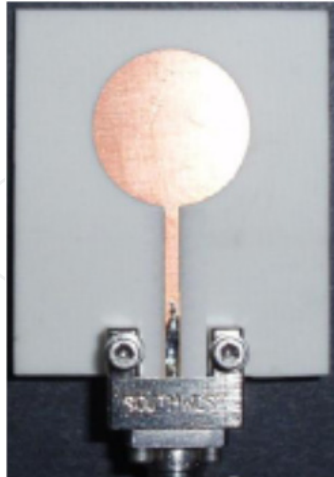

Figure 7. The prototype of simple fed CDM antenna

8. Conclusions

The objective of this chapter is to provide the fundamentals of UWB transceiver systems so that the general readers can be able to easily grasp some of the ideas in transceiver design for ultra-wideband communications. The chapter briefly describes signaling and modulation techniques, UWB transceiver system architecture, UWB antennas. Devices used for this exciting technology have become small, low power and low cost which in turn will accelerate their widespread use in indoor communications.

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