A Low Complexity Ultra-Wideband, Orthogonal Frequency Division Multiplexing Communication System

Emil NOVAKOV
Institut de Microélectronique, Electromagnétisme et Photonique (IMEP-LAHC), MINATEC – 3 parvis Louis Néel, B.P. 257, 38016 Grenoble, France
novakov@minatec.grenoble-inp.fr

Abstract

The present paper describes an Ultra-Wideband (UWB) communication system based on the Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme. The system uses a small number of sub-carrier frequencies which allow the straightforward implementation of the OFDM modulator and demodulator without the use of Discrete Fourier Transform (DFT). An experimental RF transceiver based upon the proposed method was tested. An RF band ranging from 4.2 – 4.8 GHz was used. The transceiver has a demonstrated operational line-of-sight communication range of 3 m for a data rate of up to 40 Mbit/s. This system is well adapted for implementation in a low-complexity and low-power integrated circuit.

1. Introduction

The OFDM is a very popular modulation method which is mainly used in high data rate radio communications. During the last 15 years, many wireless standards have adopted this transmission scheme (802.11a/g/n, WiMax, DVB T/H, DAB as well as the 4th generation cellular communication system - LTE). The main advantage of the OFDM over single carrier frequency communication is its ability to work in dense multi path environments and to cope with changing frequency selective propagation channels. This feature makes the OFDM technology ideally suitable for use in offices and indoor environments.

The Ultra-Wideband data communication is based upon techniques that spread radio wave energy over a very wide frequency band and transmit signals which have very low power spectral density (PSD). Current UWB spectrum regulations define the UWB in terms of spectral allocation and do not stipulate any particular radio transmission technology. The United States’ regulations allow UWB devices to operate in an unlicensed 3.1 – 10.6 GHz frequency band whilst in Europe only the 4.2 – 4.8 GHz and 6 - 8.5 GHz bands are authorized. The maximum EIRP PSD is limited to -41.3 dBm/MHz. In the 4.2 – 4.8 GHz band the maximum available power is -13.5 dBm. This means the UWB communications can only be used for short distances and their natural domain of application is the Personal Area Networking (PAN). Actually there are two basic classes of UWB systems – the impulse-radio system and the continuous (or multi-band) system [1]. The IEEE 802.15.4a standard defines a physical layer suitable for impulse radio low data-rate and medium data-rate communications. Continuous multi-band systems are based upon the OFDM modulation scheme and specified by the ECMA 368/369 standard and promoted by the WiMedia alliance [2]. The standard targets the very high data rate applications (480 - 1024 Mbit/s) mainly related to computer communications (wireless USB) or multimedia wireless data streaming. WiMedia UWB – OFDM uses a frequency band of 528 MHz. Each band is divided into 128 sub carriers spaced 4.125 MHz apart. The structure of the RF front-end and the base-band layer is very complex. The OFDM modulation and demodulation needs a tremendous amount of computing-intensive real-time signal processing (FFT, filtering, equalization …). The frequency and time synchronization between the transmitter and the receiver is also very complex and critical for the system performance. WiMedia compatible chip sets are available now but their power consumption ranges from the hundred mW to one Watt range and they are not suitable for low-power applications. Moreover, despite large standardization activities, development efforts and marketing strategies it seems that this standard can not receive wide market acceptance (at least not at the end of 2010).

The goal of this work was to design and test a low complexity UWB-OFDM communication system suitable for implementation in a low power integrated circuit. The system uses a limited number of orthogonal carriers. The modulation and the demodulation were implemented without the use of DFT. The system uses a non-coherent RF receiver and has relaxed synchronization constraints. The system was designed for medium data rate applications (20-40Mbit/s) for small battery powered devices.
2. The OFDM modulation

The basic idea of the OFDM modulation is to transmit a block of \( N \) bits of duration \( T_B \) in parallel, thus increasing the effective bit length by \( N \) [3]. The OFDM is in fact a “serial to parallel” communication system. The serial data flow \( D_i \) is buffered into a block of \( N \) bits \( D_{iT} \) with duration \( T = N T_B \). Each bit is modulated with a sinusoidal sub-carrier \( m_i \) chosen from a set of \( N \) orthogonal signals. The basic OFDM modulation / de-modulation process is presented in Fig. 1.

For an even number of bits \( N \), the sub-carrier set \( \{m_i\} \) can be expressed in the form:

\[
m_0 = \cos(\omega_0 t), \quad m_1 = \sin(\omega_0 t), \quad m_2 = \cos(2\omega_0 t), \quad m_3 = \sin(2\omega_0 t) \ldots \quad m_{N-1} = \cos[(N/2)\omega_0 t], \quad m_N = \sin[(N/2)\omega_0 t]
\]  

(1)

The signals are mutually orthogonal over the time interval \([0, T]\) i.e.:

\[
\int_0^T m_i m_j dt = 0 \quad \text{for } i \neq j
\]  

(2)

This also implies the condition: \( \omega_0 = k2\pi/T \) where \( k \) is an integer. As the signals \( m_0 \) and \( m_1 \) are in quadrature the elements in the dashed block form a quadrature amplitude modulator (QAM).

The “parallel block” length is chosen such that \( T \) is greater than the radio propagation channel maximum delay spread \( T_D \). In presence of multiple propagation channels the adjacent block will overlap thus creating an inter-block (or inter-symbol) interference (ISI). To avoid this problem and to protect the transmission against ISI a guard time interval \( (T_G) \) can be inserted between adjacent data blocks. The guard time interval can be either in the form of zero-paging or a cyclic prefix. \( T_G \) is chosen such that it is longer than the delay spread \( T_D \).

Instead of modulating individual bits \( D_i \), it is possible to substitute \( D_{iT} \) with a symbol. The symbol is a set of bits \( \{D_i\} \) encoded with particular signal amplitude. In this case many bits can be encoded on every sub-carrier. In practice different encoding schemes can be used (BPSK, QPSK, nQAM ...). The base-band modulation / demodulation can be performed by using a discrete Fourier transform (DFT). The Fast Fourier Transform (FFT), the fast algorithm for computing the DFT, allows the realization of systems with hundreds, even thousands of sub-carriers.

The complete implementation of all OFDM features (sub-carrier modulation, DFT, cyclic prefix, receiver synchronization, equalization ...) is very complex and is not suitable for low-power applications. Nevertheless it is possible to perform a simplified implementation of the OFDM providing trade off between complexity, power consumption and performances.
3. System architecture

The block diagram in Fig.2 shows the structure of the proposed UWB-OFDM transceiver. A digital divider block generates a set of orthogonal sub-carrier square wave’s $m_i$. The sub-carrier signals can be written as:

$$m_0 = \text{sgn}[\cos(\omega_0 t)] , \quad m_1 = \text{sgn}[\sin(\omega_0 t)] , \quad m_2 = \text{sgn}[\cos(2\omega_0 t)] , \quad m_3 = \text{sgn}[\sin(2\omega_0 t)]$$

(3)

where sgn[ ] denote the signum function. These signals satisfy the condition (2) and are mutually orthogonal. Nevertheless it should be stressed that for digital signals in the form (3) the orthogonality is valid only for a set of frequencies $\omega_0, 2\omega_0, 4\omega_0, \ldots, 2^n\omega_0$.

The multiply function is realized with an Exclusive OR logic gate (XOR) followed by a level converter (LC). LC in reality removes the continuous component of the digital signal. The low pass filter (LP) eliminates the higher harmonics of the data modulated sub-carrier’s square wave thus generating a sinusoidal output signal. This is necessary to enable the control of the overall bandwidth of the transmitted signal. A constant offset voltage $U_0$ is added to the OFDM signal.

$$S = U_0 + D_{oT} \cos(\omega_0 t) + D_{sT} \sin(\omega_0 t) + D_{2T} \cos(2\omega_0 t) + D_{3T} \sin(2\omega_0 t)$$

(4)

After the level conversion $D_j$ in equation (4) can take values in the set {+1, -1} and in fact the system realized with the blocks XOR, LC and LP acts as a phase modulator (PSK) for the data bit.

The switch SW inserts the guard time interval $T_G$. During the time period $T$ the complete OFDM signal $S$ is AM modulated with the carrier frequency $\omega_C$. The offset $U_0$ is chosen to achieve an amplitude modulation index close to 100%. The complete AM signal is fed to the power amplifier PA and the transmitter antenna. During the guard interval $T_G$ there is no RF transmission. This system transmits the carrier frequency $\omega_C$ only during the interval $T$. Regenerating the carrier signal in the receiver of an impulse communication system is rather difficult. An important advantage of the AM transmission scheme is the possibility of using a non coherent detection thus greatly simplifying the receiver design. The receiver is composed of a channel band-pass filter (BPF), a low noise amplifier (LNA) and a simple amplitude detector. The AM demodulated signal is sent to the OFDM decoder as well as to the synchronization block. This block extracts the signal $T$ and regenerates the sub-carrier signals $m_{SR}$ in phase with $T$. When the synchronization is locked on: $m_{SR} = m_{SS}$. The receiver uses digital sub-carrier square wave signals as they are described by (3). These signals are also generated in the synchronization block by a digital divider. This approach is possible because the signals set $\{m_i\}$ expressed by equation (1) are orthogonal to the signal set $\{m_{SS}\}$ defined by equation (3).

![Fig. 2 System architecture of the UWB-OFDM transceiver](image-url)
4. Experimental results and conclusion

The proposed system was experimentally tested. The transmitter was emulated with a Tektronix AWG7000B - Arbitrary Waveform Generator (AWG). The complete signal \( S_{SR} \) was generated from a MATLAB simulation of the transmitter block. A set of 4000 random bits \( D \) was encoded. \( S_{SR} \) is generated with 8 bit amplitude resolution and sampling time of 41.66 ps (24 GHz sampling rate). The carrier frequency \( f_c \) \( \left( f_c = \frac{c}{2\pi} \right) \) is fixed at 4.5 GHz. The simulated signal is loaded in the AWG and continuously replayed. In an indoor environment the experimental measurements show the propagation channel delay spread is less than 50ns [4]. For a transmitter – receiver separation distance of less than 10 m, the most probable RMS value of the channel delay spread in the range 10-15 ns. For this reason the \( T \) and \( T_G \) were set to 50 ns. The total frame duration is \( T_F = T+T_G = 100ns \). The system modulates 4 data bits in parallel and the maximum achievable data rate on the radio interface is 40 Mbit/s (data plus synchronization). The sub-carrier frequency \( f_0 \) is fixed to 100MHz. The bandwidth of the RF signal is approximately:

\[
B \approx 2\left(Pf_0 + 1/T \right)
\]

where \( P = N/2 \) is the number of sub carrier frequencies, In our case \( P = 2, T = 50ns \) and \( B \approx 440 \text{ MHz} \). Following the FCC/EC UWB regulations the maximum PSD was limited to -41.3dBm/MHz (EIRP).

The receiver was built around an UWB integrated circuit designed for a previous development [5]. The IC’s UWB RF receiver is composed on a LNA, a detector, a low pass filter, a variable gain amplifier and a threshold detector (dashed block in Fig. 2). All these parts were reused for the test system. Part of the base band circuit was implemented on a FPGA. On the left side of Figure 3, a photograph of the test system is shown. A set of bit error rate (BER) measurements were made with direct visibility between transmit and receive antennas in indoor environment (Lab room). The results are shown in the graph on the right side of Figure 3.

This work demonstrates the feasibility of a relatively simple UWB-OFDM communication system. A reliable link in LOS mode was achieved at 40 Mbit/s at a distance of 3 m with a BER of \( 10^{-5} \) and without forward error correction code (FEC). For a small number of sub-carriers, the direct implementation of the OFDM modulation scheme can lead to the design of low power medium data rate (10 – 40 Mbit/s) integrated circuits.

5. References

2. WiMedia Alliance [Online]. Available at: http://www.wimedia.org