Ultra-Wideband for Multiple Access Communications

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ABSTRACT

Ultra-wideband wireless communications techniques have many merits, including an extremely simple radio that inherently leads to low-cost design, large processing gain for robust operations in the presence of narrowband interference, covert operations, and fine time resolution for accurate position sensing. However, there are a number of challenges in UWB receiver design, such as capturing multipath energy, intersymbol interference especially in a non-line-of-sight environment, and the need for high-sampling-rate analog-to-digital converters. In this article we provide a comprehensive review of UWB multiple access and modulation schemes, and their comparison with narrowband radios. We also outline issues with UWB signal reception and detection, and explore various suboptimal low-complexity receiving schemes.

INTRODUCTION

Modern communication theory was originated from the attempts of communication engineers who wanted to understand what they were doing in the most general terms. The limits of digital wireless communications systems depend primarily on four basic laws and their underlying theories, attributed to Maxwell and Hertz, Shannon, Moore, and Metcalfe. The first two laws are laws of nature, while the last two are laws of behavior. The order is in the sequence of their discovery and importance. As the field of wireless communications has matured, emphasis and immediate relevance have shifted gradually downward in the list. Without an appreciation for Maxwell and Hertz's theories, there would be no controlled wireless propagation of electromagnetic waves. Without an understanding of Shannon's theories, efficient use of the spectrum through sophisticated signal processing could not have been achieved. Ultra-wideband (UWB) is experiencing this shift, probably from the first two laws, while narrowband communications has shifted to the last two laws.

Although often considered a recent breakthrough in wireless communications, UWB has actually experienced well over 40 years of technological development. The physical cornerstone for understanding UWB pulse propagation was established by Sommerfeld a century ago (1901) when he attacked the diffraction of a time domain pulse by a perfectly conducting wedge. In fact, one may reasonably argue that UWB actually had its origins in the spark gap transmission design of Marconi and Hertz in the late 1890s. In other words, the first wireless communications system was based on UWB. Due to technical limitations, narrowband communications was preferred to UWB. Much like spread spectrum or code-division multiple access (CDMA), UWB followed a path with early systems designed for military covert radar and communications. After accelerating development since 1994 when some of the research activities were unclassified, UWB picked up its momentum after the Federal Communications Commission (FCC) Notice of Inquiry in 1998. Interest in UWB was sparked when the FCC issued a Report and Order in February 2002 allowing its commercial deployment with a given spectral mask requirement for both indoor and outdoor applications.

The main limiting factor of UWB wireless systems is power spectral density rather than bandwidth. Thus, the initially targeted application was short-range (< 10 m) high-data-rate (> 100 Mb/s) within IEEE 802.15.3a. Due to implementation limitations, systems with moderate range (100–300 m) and low data rates (less than a few megabits per second) have received significant attention since late 2003 within IEEE 802.15.4a. In addition, UWB applications should also include safety/health monitoring, personnel security, logistics, industrial inventory control, industrial process control and maintenance, home sensing, control, and media delivery. In this article our goal is to provide a comprehen-

 0163-6804/05/$20.00

sive review of UWB multiple access and modulation schemes, and their comparison with narrowband radios. We will also outline issues in UWB signal reception and detection, and explore various suboptimal low-complexity receiving schemes. The rest of the article is organized as follows. We describe the basics of pulsed UWB modulation schemes. Multiple access approaches employing pulsed UWB technologies are presented. UWB receiver designs and challenges are discussed, followed by conclusions.

MODULATION SCHEMES

Based on FCC regulation, pulsed UWB is a form of bandpass communications. The transmitter sends pulses with a bandwidth (10 dB) that is at least 500 MHz and edge frequencies within 3.1–10.6 GHz [1].

MULTIBAND DESIGN

The major reasons for the standards body (IEEE 802.15.3a) to adopt a multiband scheme are:

- Spectrum flexibility/agility: regulatory regimes may lack large contiguous spectrum allocation; spectrum agility may ease coexistence with existing services.
- Energy collected per RAKE finger scales with longer pulse widths used, which prefers fewer RAKE fingers.
- Reduced bandwidth after downconversion mixing reduces receiver power consumption and linearity requirements.
- A fully digital solution for signal processing is more feasible than a single-band solution for the same occupied bandwidth.
- Transmitter pulse shaping is made easier; longer pulses are easier to synthesize and less distorted by integrated circuit (IC) package and antenna properties.
- It is capable of utilizing frequency-division multiple access (FDMA) for severe near-far scenarios.

The Multiband Pulsed Scheme — The main disadvantage of narrow time domain pulses is that building radio frequency (RF) and analog circuits as well as high-speed analog-to-digital converters (ADCs) to process signals of extremely wide bandwidth is challenging, and usually results in high power consumption [2]. Collection of sufficient energy in dense multipath environments requires a large number of RAKE fingers. The pulsed multiband approach can eliminate the disadvantages associated with large front-end processing bandwidth by dividing the spectrum into several subbands. The advantage of this approach is that the information can be processed over much smaller bandwidth, thereby reducing the design complexity and power consumption, lowering cost, and improving spectrum flexibility and worldwide compliance. However, it is difficult to collect significant multipath energy using a single RF chain. In addition, there are very stringent frequency switching time requirements (< 100 ps) at both transmitter and receiver.

The Multiband OFDM Scheme — Multipath energy collection is an important issue as it is a major factor that determines the range of a communication system. The multiband orthogonal frequency-division multiplexing (OFDM) system transmits information on each subband. This technique has nice properties including the ability to efficiently capture multipath energy with a single RF chain. The drawback is that the transmitter is slightly more complex because it requires an inverse fast Fourier transform (IFFT), and the peak-to-average ratio may be higher than that of pulse-based multiband approaches. It seems to be very challenging for both the pulse-based and OFDM-based multiband solutions to meet the target costs imposed by the market.

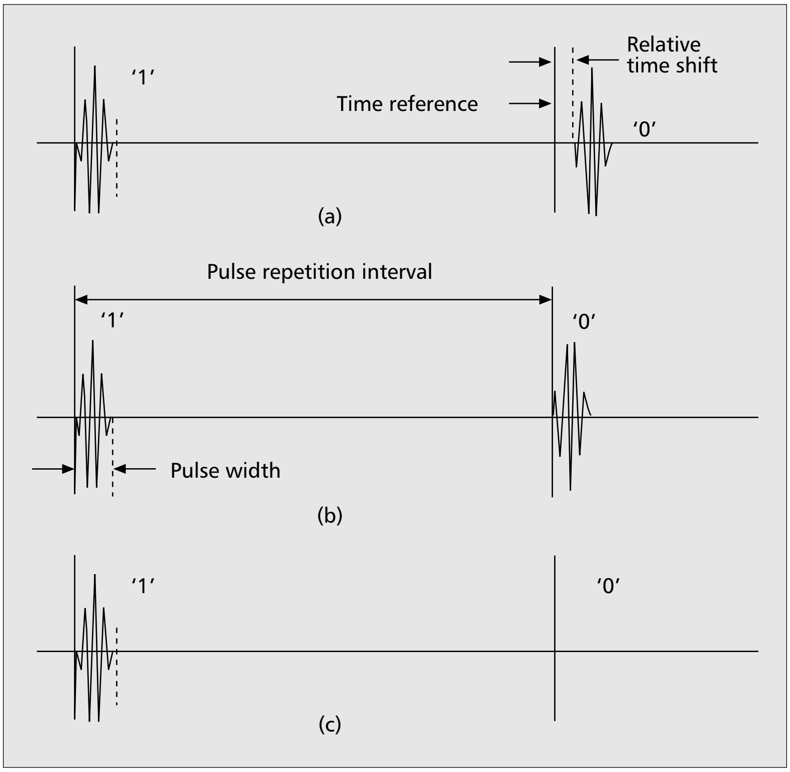

Figure 1. *UWB modulation options: a) binary PPM; b) binary PAM; c) on-off keying.*

MODULATION OPTIONS

In choosing modulation schemes for UWB systems, one must consider a number of aspects such as data rate, transceiver complexity, spectral characteristics, robustness against narrowband interference, intersymbol interference, and error performance. For pulsed UWB systems, the widely used forms of modulation schemes include pulse amplitude modulation (PAM), on-off keying (OOK), and pulse position modulation (PPM). To satisfy the FCC spectral mask, passband pulses are used to transmit information in pulsed UWB systems. Although these passband pulses could be obtained by modulating a baseband pulse using a sinusoidal carrier signal, the term binary phase-shift keying (BPSK) is still somewhat imprecise in the context of pulsed UWB signaling as the carrier-modulated baseband pulse is usually treated as a single entity, the UWB pulse shape.

The three modulation schemes mentioned above are illustrated in Fig. 1. For a single-user

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system with binary PPM signaling, bit 1 is represented by a pulse without any delay and bit 0 by a pulse with delay relative to the time reference. A major factor governing the performance of this system, like any other PPM-based system, is the set of time shifts used to represent different symbols. The most commonly used PPM scheme is the orthogonal signaling scheme for which the UWB pulse shape is orthogonal to its time-shifted version. There also exists an optimal time shift for an M-ary PPM scheme. The time shifts for both the orthogonal and optimal schemes depend on the choice of UWB pulse $p(t)$. For binary PAM signaling, information bits modulate the pulse polarity. For OOK signaling, information bit 1 is represented by the presence of a pulse, and no pulse is sent for bit 0.

Binary PAM and PPM schemes have similar performance. The OOK scheme is less attractive than PAM or PPM because of its inferior error performance in the same environment. However, if receiver complexity is the main design concern, a simple energy detection scheme can be applied to OOK signals, resulting in a receiver of lowest achievable complexity. Power spectral density (PSD) of the modulated UWB signal must satisfy the spectral masks specified by spectrum regulating agencies. In the United States, the spectral mask for indoor applications specified by the FCC starts from 3.1 to 10.6 GHz. OOK and PPM signals have discrete spectral lines. These spectral lines could cause severe interference to existing narrowband radios, and various techniques such as random dithering could be applied in PPM to lower these discrete spectral lines and smooth the spectrum. Because of the random polarities of the information symbols, the PAM scheme inherently offers smooth PSD when averaged over a number of symbol intervals. In this sense, PAM signaling is attractive.

Multiple Access Schemes

Multiple access communications employing pulsed UWB technologies has drawn significant research interest. Various multiple access schemes and their performance have been reported in the literature [3, 4]. Time hopping (TH) has been found to be a good multiple access technique for pulsed UWB systems [4], and various modulation options for TH UWB systems are discussed in terms of their spectral characteristics and hardware complexities in [5]. Direct sequence (DS) spreading is also an attractive method for multiple access in UWB systems. Performance of a DS-UWB system with PAM was analyzed in [3]. Since pulsed UWB systems are inherently spread spectrum systems, the use of spreading codes in DS-UWB systems is solely for accommodating multiple users.

Time Hopping for Multiple Access

In pulsed UWB systems, the pulse duty cycle is very small. Thus, the transmitter is gated off for the bulk of a symbol period. Multiple access can be implemented by employing appropriately chosen hopping sequences for different users to minimize the probability of collisions due to multiple access. In TH UWB, each frame is subdivided into N_h chips of duration T_c. Each user (indexed by k) is assigned a unique pseudo-random time shift pattern, $\{h_{k,n}\}$, $0 \le h_{k,n} < N_h$, called a TH sequence, which provides an additional time shift to each pulse in the pulse train. The nth pulse undergoes an additional shift of $h_{k,n}T_c$ s, where chip duration T_c is also the duration of an addressable time delay bin [4]. The addressable TH duration must be strictly less than the frame time. For TH PPM, information data are carried by the additional time shift τ. For TH PAM, information data are transmitted by changing the amplitude of the time-hopped pulse. With binary signaling, the transmitted TH PAM or TH PPM signal of the kth ($k = 1, \ldots, K$) user can be written in a general mathematical form as

$$S_k(t) = \sum_{n=-\infty}^{\infty} \sqrt{E_b}\, b_{k,n}^0\, p\left(t - nT_b - h_{k,n}T_c - \frac{\tau}{2}\left(1 - b_{k,n}^1\right) \right) \quad (1)$$

where E_b is the transmitted energy per bit, n is the bit index, T_b is the bit interval, $p(t)$ is the UWB pulse, and b_n^0, b_n^1 are information bits (may have been converted to non-return-to-zero form). For TH-PAM, $b_{k,n}^1$ is set to 1 and $b_{k,n}^0 \in \{-1, 1\}$ carries information. For TH PPM, $b_{k,n}^0$ is set to 1 and $b_{k,n}^1 \in \{-1, 1\}$ carries information. The pseudo-random hopping sequence $\{h_{k,n}\}$ is used to identify the kth user.

Direct Sequence for Multiple Access

Direct sequence can also be used for multiple access in a PAM-UWB or PPM-UWB system. In such a system, each symbol is represented by a series of pulses that are pulse-amplitude-modulated by a chip sequence. Input symbols are modulated onto either the amplitude or the relative positions of each sequence of pulses.

For *binary* signaling, the transmitted signal for direct-sequence PAM or direct-sequence PPM signals of the kth ($k = 1, \ldots, K$) user can be written in a general mathematical form as

$$S_k(t) = \sum_{n=-\infty}^{\infty} \sqrt{E_b}\, b_{k,n}^0\, p\left(\sum_{i=0}^{N_c-1} a_{k,i}\, p\left(t - nT_b - iT_c - \frac{\tau}{2}\left(1 - b_{k,n}^1\right) \right) \right) \quad (2)$$

where E_b is the transmitted energy per bit (assuming the total energy of N_c pulses is normalized to unity), T_c is the chip duration, $a_{k,i} \in \{-1,1\}$ is the ith chip of the kth user, N_c is the number of chips used to represent one symbol, and $b_{k,n}^0$, $b_{k,n}^1 \in \{-1,1\}$ are the information bits of the kth user. The N_c-chip PN sequence, $\{a_{k,0}, \ldots a_{k,(N_c-1)}\}$, is used to identify the kth user. It must be ensured that the pulse duration T_p is less than the chip duration T_c, and N_cT_c must be less than the symbol repetition interval.

For binary DS-PPM systems, information bit 1 is represented by a frame of pulses without any delay, and information bit 0 is represented by the same frame of pulses but with a delay τ relative to the time reference. Let K be the number of users in the system. Thus, $b_{k,n}^0$ is set to 1 and the information bit of the kth user is carried by $b_{k,n}^1$ in such a system. For binary DS-PAM signals, $b_{k,n}^1$ is set to 1 and the information bit of the kth user is carried by $b_{k,n}^0$.

Similar to single-user PPM signaling, the most commonly used DS-PPM scheme is the orthogonal signaling scheme for which the DS spread UWB pulse is orthogonal to its time-shifted version. There also exists an optimal time shift for a DS-PPM scheme. Let the sequence of pulses used to represent bits 1 and 0 of the kth user be $S_{k,1}(t)$ and $S_{k,0}(t) = S_{k,1}(t - \tau)$, where $S_{k,1}(t)$, $S_{k,0}(t)$ have unit energy (i.e., $\int_{-\infty}^{\infty} S_{k,j}^2(t)dt = 1$, $j = 0, 1$). For the orthogonal signaling scheme, τ_{ortho} is chosen to be such that $\int_{-\infty}^{\infty} S_{k,1}(t)S_{k,1}(t - \tau_{ortho})dt = 0$. The orthogonality condition may be met for a number of choices of τ ($0 < \tau < T_b$), and the minimum of those values is usually chosen as the time shift. For optimally spaced signaling, the time shift τ_{opt} is chosen in the range $0 < \tau_{opt} < T_p$ such that cross-correlation between the symbols is minimized.

UWB Receiver Design and Challenges

Channel Models

UWB represents a major shift in design considerations in terms of signal propagation. A conventional narrowband system typically operates in less than 20 MHz bandwidth (GSM, wideband CDMA [WCDMA], IEEE 802.11). However, UWB systems operate using up to 7.5 GHz bandwidth. Although current implementations preclude direct use of such large bandwidth, one must understand its significance. A radical difference of a UWB channel from a narrowband channel is the number of resolvable multipaths. With a 0.167 ns multipath resolution (about 6 GHz bandwidth), more than 30 significant paths exist in a typical indoor environment. Collecting all multipath energy for reliable detection represents a major challenge for UWB receivers. In addition, maximum excess delay values of greater than 60–70 ns (root mean square, RMS, delay of 20–25 ns) were commonly observed for indoor environments. For high-speed short-range applications such as 100 MHz (10 ns symbol repetition interval), the multipath delay will lead to at least six or seven overlapping symbols. This symbol overlapping requires mitigation via (symbol-rate) equalization followed by the matched filter (RAKE receiver).

Another potential problem of UWB is per-path pulse distortion. Mathematically the generalized channel model can be expressed by

$$h(\tau) = \sum_{n=1}^{L} A_n h(\tau) * \delta(\tau - \tau_n),$$

where L generalized paths are associated with amplitude A_n, delay τ_n, and per-path impulse response $h_n(\tau) \cdot h_n(\tau)$ represents an arbitrary function that has finite energy. Symbol * denotes convolution, and $\delta(x)$ is the Dirac Delta function. Statistical parameterization of $h_n(\tau)$ is a challenging task. Turin's model expressed as

$$h_{Turin}(\tau) = \sum_{n=1}^{L} A_n \delta(\tau - \tau_n)$$

is a special case of $h(\tau)$ defined above when $h_n(\tau) = \delta(\tau)$. Pulse distortion is not as severe for indoor applications such as those targeted by IEEE 802.15.3a, but it could cause serious problems for IEEE 802.15.4a that adopts a special form of $h(\tau)$ [6]. In [6] pulse distortion is the same for each path (i.e., $h_n(\tau) = h_0(\tau)$ for all n). Note that in [6] the older notion of frequency dependency [7, earlier references therein] is used to characterize pulse distortion. From a theoretical point of view, the notion of per-path pulse distortion provides a framework to unify the deterministic physical models of time domain electromagnetics. The physics-based unified model forms a new basis for future system and signal processing models, as Turin's model does for narrowband systems. The physical origins of pulse distortion due to diffraction of a UWB pulse by some simple structures were well understood.

Different from a narrowband system, a UWB system must include antennas as pulse shaping filters. In addition, antennas act as different pulse shaping filters for different angles. Due to unpredictable arriving angles of multipath, antennas "distort" or "shape" the transmitted pulses differently for different paths, as experimentally observed. Thus, both antennas and propagation environments suggest channel model $h(\tau)$. One difficulty is to decouple the effect of highly dispersive antennas and highly dispersive propagation environments such as dense urban. There is an ongoing demand for the solution of basic pulse propagation problems to permit propagation models to be based on sound physical principles. This is called the physics-based modeling framework [7]. The coarse but rapid results produced by empirical models represent another extreme. With the high resolution of UWB signals and small area of interest, there is an increasing trend toward the physics-based framework, which facilitates the understanding of the theoretical foundation and ultimate limits imposed by electromagnetic wave theory and communications theory.

Interference Issues

Interference is one of the major issues in the receiver design for a pulsed UWB multiple access system. The first problem is intersymbol interference (ISI) caused by multipath delay. In order to illustrate the ISI problem, Fig. 2 shows the simulated received signals when two pulses of 0.5 ns duration spaced 25 ns apart are transmitted and go through a multipath channel. The channel RMS delay spread is 25 ns, and it is assumed there is a resolvable path in each bin of one bit duration. For a channel with a given delay spread, a higher data rate will result in a lower pulse repetition interval, causing a larger amount of ISI. A complex equalizer is probably impractical in a real system. Thus, ISI, rather than the bandwidth, will eventually limit the achievable data rates in a pulsed UWB system.

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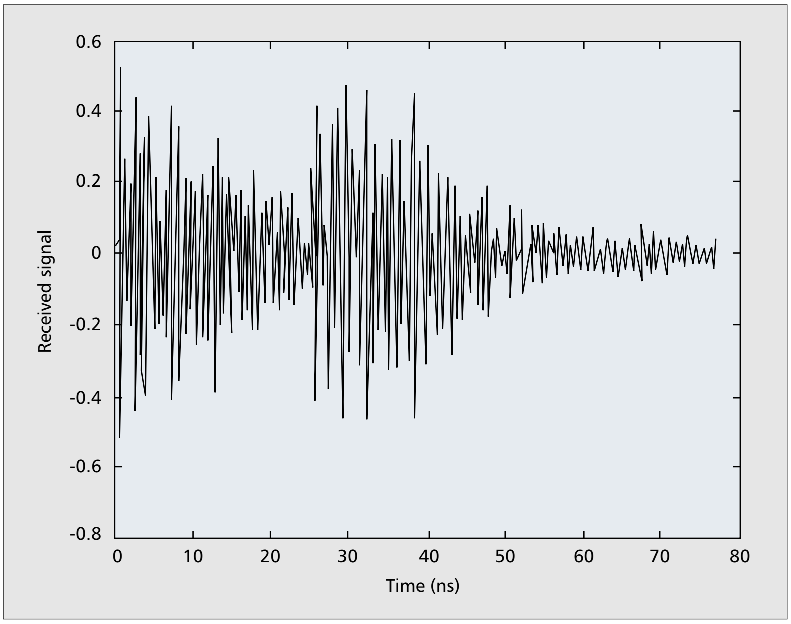

Figure 2. *A simulated received signal for two transmited UWB pulses (0.5 ns duration) spaced 25 ns apart.*

In a multi-user scenario, multiple access interference (MAI) for either the DS-UWB or TH-UWB system must be considered, just like in a conventional CDMA system. Since a series of pulses are used to represent one symbol in a DS-UWB (PAM or PPM) system, many multipath components are received within the observation window of a particular symbol, causing interpath interference (IPI). If a RAKE-type receiver is employed, each path at the input of the combiner is corrupted by its preceding and following paths, which eventually limits performance. For TH multiple access, a larger number of users in the system causes a higher probability of collision. Also, the randomly hopped chips placed at the latter portion of a symbol interval may cause severe ISI to other users. Finally, a system's robustness to intentional jamming is also an important design consideration [8].

Optimum Receiver Structure

We incorporate the per-path impulse response into the optimal receiver when ISI is present. It has been shown for a narrowband system that the optimum receiver structure is illustrated in Fig. 3.

The received signal $r(t) = y(t) + n(t)$ first passes through the matched filter $y^*(-t)$ followed by a sampler at a sampling rate of $1/T_s$. The composite signal $y(t)$ is expressed as $y(t) = x(t) * h(t)$, where $x(t)$ is the transmitted signal and $h(t)$ is the generalized channel model. The sampled sequence is further processed by a maximum likelihood sequential estimator (MLSE) detector that was first studied by Forney (1972). This receiver structure is optimal in terms of minimizing the probability of transmission error in detecting the information sequence. If $y(t)$ is of finite energy, the structure of Fig. 3 can immediately be applied to UWB receiver design.

Figure 4 shows the normalized auto-correlation function of the impulse response of a channel $R_{hh}(t)/R_{hh}(0)$. It is interesting to notice that the first peak has an energy above 50 percent of the total energy. We can think of each pulse as a chip for a spread spectrum system, and the channel impulse response can be regarded as a pseudo-noise code where the width of multipath delay spread corresponds to the length of the PN code. This observation intuitively suggests that it is simpler to base the detection on the auto-correlation $R_{hh}(t)$ rather than the noisy $h(t)$. If the first tap is used (shown in Fig. 4), the collected energy is above 50 percent of the total energy.

Suboptimum Receiver Structures

Let us simplify optimum receiver structures in two directions. First, the matched filter can be simplified in a suboptimum manner. The output of the matched filter is the auto-correlation of $y(t)$. Since the per-path pulse waveform has been included in the channel impulse, the resultant matched filter is sometimes called a generalized RAKE receiver structure, of which Altes' receiver structure is a special case. When per-path pulse distortion is included, the suboptimum implementation of the matched filter is the RAKE receiver structure. In the absence of per-path pulse distortion, the matched filter is identical to the RAKE receiver of Price and Green (1958). The transmitted reference scheme with an auto-correlation receiver [9], the differential scheme with energy detector [10], and time reversal method [11] are special suboptimum forms to approximate the auto-correlation of $y(t)$. Second, suboptimum linear equalizers such as zero-forcing, decision feedback, and adaptive equalization can be used to replace the optimum MLSE. The receiver structure of RAKE plus MMSE equalizer, as proposed in IEEE 802.15.3a, is a simplified implementation of the optimum receiver shown in Fig. 3.

It is found that per-path pulse distortion affects the system performance through the output of the matched filter. Interpulse overlapping combined with per-path pulse distortion makes receiver design very challenging. With suitable manipulation, the structure of Fig. 3 and its suboptimum forms are valid for multi-user detection. The structure of Fig. 3 forms a unified framework that connects the physics-based time domain channel model [7] with detection theory. If the number of overlapping symbols is less than 10, the MLSE (in Fig. 3) may even be feasible for state-of-the-art signal processing capability.

Receiver Challenges

High-Sampling-Rate ADC — Most existing detection schemes require an ADC that operates at a minimum of the Nyquist rate. For high-performance design, the sampling rate is in the multi-gigahertz range for UWB signaling (minimum bandwidth is 500 MHz). In addition to the extremely high sampling frequency, the ADC must support a relatively high resolution (e.g., greater than 4-6 bits) to resolve signals from narrowband interference. Such a speed mandates the use of an interleaved flash ADC, which tends to be power hungry with a power scaling exponentially increasing with bit precision. Although achievable with today's complementary metal oxide semiconductor (CMOS) technology, such an ADC must be avoided for low-power operations. One technique to avoid using such a high-speed ADC is to implement the correlator in the analog domain. One technical challenge associated with the analog implementation method is the difficulty in obtaining the receiver template waveform and deriving the precise timing of symbols and received paths. In the digital implementation, a bank of correlators that are delayed relative to one another by a fraction of the pulse duration can be applied to correlate with the received digitized signal, and the local peaks corresponding to the possible received pulses are located. With analog implementation, this is difficult to achieve because some sort of analog delay units are needed, and novel multipath tracking methods are needed. Another approach is to represent the samples using fewer bits. One bit (monobit) representation of samples, a traditional approach, finds new application in UWB to reduce ADC speed.

Multipath Capture — One of the advantages of pulsed UWB communication is its ability to resolve individual multipath components. However, the large number of resolvable paths in such a system makes it unrealistic to employ the traditional RAKE receiver to capture a significant portion of the energy contained in the received multipath components, and most existing receivers must resort to a partial or selective RAKE for multipath combining. A partial or selective RAKE can practically combine up to a few paths, which represent only a small percentage (e.g., less than 10 percent) of the total received signal energy in a non-line-of-sight (NLOS) environment. A RAKE with more than three to five paths will lead to an exponential increase in complexity because multipath acquisition, multipath tracking, and channel estimation consume too much processing resources. The insufficient multipath energy captured by the receiver results in poor system range and almost no tolerance to ISI caused by multipath delay. Suboptimal schemes such as the transmit reference [9] or differential scheme [10] can perform successful multipath energy capture and detection without requiring channel estimation. The primary drawback of these receivers is the significant performance degradation associated with employing noisy received signals as the reference signals for data detection. The net result is that such a receiver could perform much worse than a partial or selective RAKE receiver, which implements only a small number of fingers. The decision feedback autocorrelation receiver [12] overcomes the drawbacks of these receivers. In this scheme, the received signal waveform is delayed using analog delay units. The respective symbol decisions are applied to data-demodulate the outputs of these delay units, which are then summed up, forming the receive template waveform. The template waveform quality can be adjusted by changing the number of symbol intervals over which the received waveform is averaged. However, the analog delay units needed to derive the receiver template could be costly in implementation.

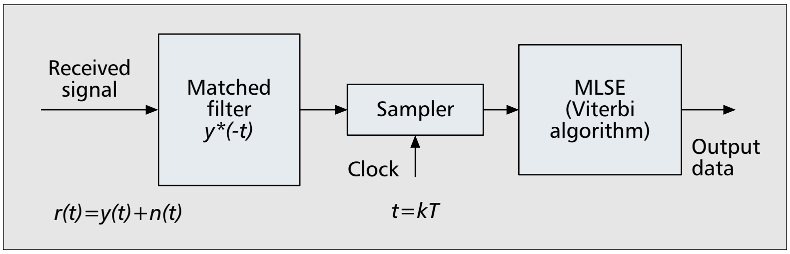

Figure 3. *Optimal receiver structure in the presence of ISI in an additive white Gaussian noise channel.*

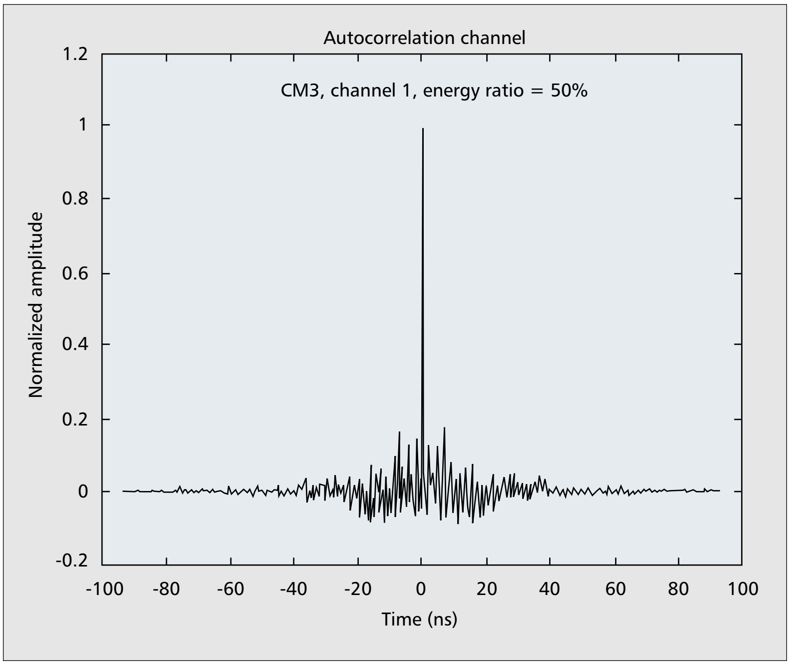

Figure 4. *Auto-correlation of a channel impulse response* $R_{hh}(t) = h(t) * h(-t)$ *for a CM3 channel.*

In a time reversal scheme [11] the channel impulse response is used as a prefilter at the transmitter. After the encoded information bits pass through the channel, the response of the channel is the auto-correlation of the channel impulse response as shown in Fig. 4. A pilot signal can be used to sound the channel such that the transmitter has the channel impulse response available for precoding. This scheme is used to shift the design complexity from the receiver to the transmitter [11]. In the time reversal scheme, a signal is precoded such that it focuses in both time and space at a particular receiver. Due to temporal focusing, the received power is concentrated within a few taps, and the task of equalizer design becomes much simpler than without focusing.

FUTURE OUTLOOK

Industrial standards such as IEEE 802.15.3a (high data rate) and IEEE 802.15.4a (very low data rate) have been introduced based on UWB technology. Department of Defense (DOD)

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UWB systems are different from commercial systems in that mobility is a significant concern. UWB has found a new application for lower-data-rate moderate-range wireless communications, illustrated by IEEE 802.15.4a and DOD systems enabling joint communication and ranging capabilities unique to UWB. Unlike the indoor environment in 802.15.3a (wireless personal area network, WPAN), the new environments for sensors, IEEE 802.15.4a, and DOD systems will be very different, ranging from dense foliage to dense urban obstructions. Pulse-based UWB has gained momentum again for some new applications after a short setback when OFDM-based UWB was popular in IEEE 802.15.3a. The mainstream papers in the literature deal with pulse-based UWB systems. One reason may be the former was not sufficiently understood compared to OFDM. It should not be regarded as a sign that industry should favor the former. It is beyond the scope of this article to comment on the pros and cons of the two types of systems.

Most existing work regarding the CDMA system seems to still be valid. There exist some unique issues:

- Pulse distortion caused by antennas and dispersive propagation environments is critical. The challenge also comes from the fact that it is very difficult to decouple the effect of antennas with propagation environments. A typical pulse-based system usually does not have a front-end filter like its narrowband counterpart, so pulse distortion serves as a pulse shaping filtering effect that must be included in the system model
- The receiver structures need more evaluation. A RAKE structure is often suggested. When pulse distortion occurs, the generalized RAKE structure is required for optimum reception. Channel estimation and synchronization required for RAKE are too difficult for short UWB pulses, so some suboptimum alternatives are investigated. To avoid these difficulties the TR philosophy seems to be very promising, especially for the DOD's adverse environments and IEEE 802.15.4a. But the noisy template problem and weak capability to counteract intentional interference are two basic problems.
- UWB antennas are important and often require co-design with other parts of the baseband. Communications imposes stringent requirements on antennas. Low-cost omni antennas are challenging. UWB multiple antennas are rarely understood.

CONCLUSION

In this article we provide a comprehensive review of UWB multiple access and modulation schemes and compare them with narrowband radios. We also outline issues with UWB signal reception and detection, and explore various suboptimal low-complexity receiving schemes. Its focus is on balancing the treatments of theoretical and practical designs. We also mix the needs of two major different applications (IEEE 802.15.3a and 4a). The future of UWB for wireless multiple access is optimistic, simply because of the unprecedented huge chunk of unlicensed spectrum. In the long run UWB will change some basic thinking in the standard wireless textbooks. For one thing, the concept of gigabit wireless communications is enabled by UWB. One must admit that people still know little about UWB compared to its narrowband counterpart developed in the last half century.

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