System Considerations for Ultra-Wideband Wireless Networks

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Abstract- **This paper describes some general properties of ultra-wideband (UWB) communications systems and identify characteristics of UWB technology that make it an attractive solution for indoor wireless networks. This paper describes a number of different modulation and coding schemes that are possible for UWB communication systems. Based on results in the literature and additional analysis here, approaches likely to provide the best performance for wireless network applications are identified.**

I. Introduction

What is UWB? This term has begun to appear more often in the news media and in academic research, but it is still somewhat of an enigma. In some cases it is even touted as a revolutionary new technology that will offer unlimited new bandwidth for wireless communications. In order to understand this technology better, we present a general description of what constitutes a UWB system and we attempt to understand how it might be attractive for wireless networks. Although UWB technology has also been used in radar and ranging applications, here we will only address issues relevant to wireless networking applications.

Most of the UWB systems reported in the literature differ in terms of their modulation techniques, bandwidth, center frequency, pulse rate, and pulse shaping [1], [5]. Nevertheless, there are common characteristics that are shared by most devices that claim to be UWB. We examine some of these distinguishing characteristics in section II and analyze the effects of these characteristics on system-level design decisions such as modulation and coding techniques in section IV.

As a final point of introduction it is helpful to briefly note some important design issues for indoor wireless networks. Such systems will need to operate over relatively short ranges in environments with multipath interference, but will need to provide high data rates, preferably using unlicensed spectrum. Also, such systems are often used to support mobility, so they need low power dissipation to enable battery operation and, as always, low cost and complexity is an advantage.

II. Characteristics of UWB Systems

In general, UWB systems use signals that are based on trains of short duration pulses formed using a single basic pulse shape. It is this property that has led to the term "impulse radio" which is sometimes used in the literature.[1] The interval between individual pulses can be uniform or variable, and there are a number of different methods that can be used for modulating the pulse train with data for communications. One common characteristic, however, is that the pulse train is transmitted without translation to a higher carrier frequency, and so UWB is sometimes also termed "carrierless" radio. In other words, a UWB system drives its antenna directly with a *baseband* signal.

Another important point common to UWB systems is that the individual pulses are very short in duration, typically much shorter than the interval corresponding to a single bit. We can represent a general UWB pulse train signal as a sum of pulses shifted in time:

$$s(t) = \sum_{k=-\infty}^{\infty} a_k p(t - t_k) \tag{1}$$

Here $s(t)$ is the UWB signal, $p(t)$ is the basic pulse shape, and a_k and t_k are the amplitude and time offset for each individual pulse. Because of the short duration of the pulses, the spectrum of the UWB signal can be several gigahertz or more in bandwidth, overlaying the bands used by existing narrowband systems.

In anticipation of allowing such systems to be produced for general use, the FCC has proposed that UWB systems be permitted to operate on an unlicensed basis at extremely low transmit power levels under the guidelines of Part 15 of the Code of Federal Regulations. As part of this proposal the FCC has tentatively defined UWB systems as those which have bandwidths exceeding 25% of their center frequency, or 1.5 GHz, whichever is less. At the time of this writing, formal proceedings to evaluate this proposal are ongoing.[2]

Because of the limitation imposed by their extreme low power and available bandwidths of several gigahertz or more, UWB systems operate as spread spectrum systems, that is, their bandwidths are much greater than the minimum required for the effective data rate. In contrast to more common forms of spread spectrum communications such as frequency hopping or direct sequence systems, however, UWB does not rely on a spreading sequence or a hopping sequence to produce a wide bandwidth signal. Instead, it is the extremely short duration of the basic pulse that gives the system its ultra-wide bandwidth.

The extremely wide bandwidth is also the primary difference between UWB systems and conventional narrowband wireless systems. More specifically, UWB systems operate in the *power-limited regime* whereas many

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[1]The term *impulse radio* seems to be used to refer to UWB systems that use pulse-position modulation in combination with time-hopping as a multiple access technique, see [1], [2].

[2]A discussion of the UWB proceedings is beyond the scope of this paper. Specific proposals and a discussion of relevant issues can be found in the *Notice for Proposed Rulemaking* for this proceedings, FCC document number 00-163, and other public comments are available under FCC docket number 98-153.

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narrowband systems today operate in the *bandwidth-limited regime*. This fundamental difference has a significant effect on design choices for modulation and coding techniques, as we will see in later sections. Despite these differences, however, UWB system design can still be analyzed using standard tools of communications theory and we can therefore use these tools to understand what techniques will most likely lead to effective UWB systems.

III. The Consequences of Bandwidth

UWB has many advantages that make it a promising technology for indoor wireless networks. These include potential unlicensed operation, resistance to multipath interference, and low transmit power.

A. *Multipath Robustness and Ranging*

One benefit of ultra-wide bandwidth is a robustness to the effects of multipath interference. Previous work indicates that UWB signals experience a much lower variance in received signal power in the presence of multipath than do narrowband signals [3]. This effect can be understood from a frequency-domain perspective by realizing that the signal bandwidth of the UWB signal is much greater than the coherence bandwidth of the multipath channel. Any frequency-selective fades only affect a small portion of the signal power for any channel realization [10]. The wide bandwidth of UWB signals provides fine time resolution which in turn enables a receiver to resolve and combine individual multipath components, avoiding destructive interference [9].

It is the extremely fine time resolution of UWB systems that also enables the development of precise ranging capability, and much of the early development work in UWB technology was for radar applications. Although there is typically a clear distinction between communications and ranging applications, UWB technology provides the potential to easily combine the two to enable a new class of systems that use ranging information to provide new functionality for security, improved performance, or more efficient wireless networks through the use of precise range information.

B. *Relatively Low Transmit Power and Linear Scaling of Data Rate with Power*

From a communications theory perspective, perhaps the most important characteristic of UWB systems is power-limited regime operation. The impact of this is clearly seen in Shannon's equation for channel capacity:

$$C = W \log_2 \left(1 + \frac{WP_0}{WN_0}\right) \text{ bits per second} \quad (2)$$

where C is the channel capacity, W is the bandwidth in Hz, P_0 is the signal power in watts/Hz and $N_0/2$ is the noise spectral density in watts/Hz [8]. For a UWB wireless network, the bandwidth will likely be much higher than the data rate so that the system can operate at very low signal to noise ratios. This means that a UWB wireless network will be able to achieve high data rates with relatively low transmit power. A key point is that in this regime capacity increases nearly *linearly* with power, whereas in the bandwidth-limited (high SNR) regime, capacity increases only as the *logarithm* of signal power (so that linear increases in data rate require exponentially more power). This fact also highlights the importance of a power efficient modulation format in the design of a UWB system: a small disadvantage in power efficiency directly translates to a corresponding reduction in throughput.

IV. Analysis of UWB Modulation Choices

Under anticipated regulations, UWB transmit power will likely be limited by the power spectral density (PSD) of the transmitted signal (see note 2 above), affecting the choice of modulation in two ways. First, the modulation technique needs to be power efficient. In other words, the modulation needs to provide the best error performance for a given energy per bit. Second, the choice of a modulation scheme affects the structure of the PSD and thus has the potential to impose additional constraints on the total transmit power. As we compare different modulation schemes, therefore, we examine both the power efficiency and the effect of the modulation on the PSD. In the sections that follow, we examine several modulation schemes that have been proposed for UWB including pulse-position modulation (PPM) and several forms of pulse amplitude modulation (PAM) including binary phase-shift keying (BPSK) and on-off keying (OOK).

A. *Pulse-Amplitude Modulation*

In an section II we saw that the general form of a UWB signal is a simple pulse train. If we assume that pulses are uniformly spaced in time (*i.e.* the k^{th} pulse occurs at time $t = kT$), then we can simplify (1) to

$$s(t) = \sum_{k=-\infty}^{\infty} a_k p(t - kT) \quad (3)$$

where T is the pulse-spacing interval. The power spectral density of this signal, $\Phi_{ss}(f)$, is the Fourier transform of the signal autocorrelation. If we assume that the pulse weights correspond to the data bits to be transmitted and that the data are random and *i.i.d.*, then the PSD can be found following the method in [7]:

$$\Phi_{ss}(f) = \frac{\sigma_a^2}{T}|P(f)|^2 + \frac{\mu_a^2}{T^2} \sum_{k=-\infty}^{\infty} \left|P\left(\frac{k}{T}\right)\right|^2 \delta\left(f - \frac{k}{T}\right) \quad (4)$$

where σ_a^2 and μ_a are the variance and mean of the weight sequence, $P(f)$ is the Fourier transform of $p(t)$ and $\delta(f)$ is a unit impulse. This PSD in (4) has both a continuous portion and discrete spectral lines, corresponding to the first and second terms on the right-hand side. It is worth noting that the magnitude of the spectral lines depends on the mean of the weights, μ_a.

If we wish to encode the data bits using OOK, then we could use $a_k \in \{0, 2\}$ and so $\sigma_a^2 = 1$ and $\mu_a = 1$ (again assuming the data bits are random and

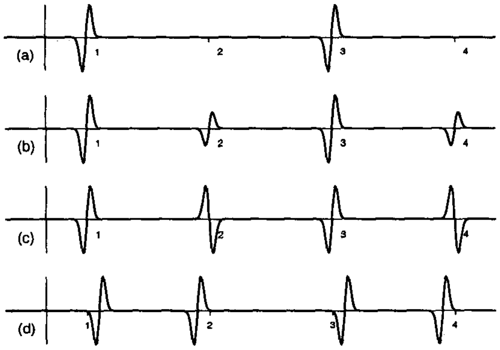

Fig. 1. Four different modulation techniques for UWB pulses showing the encoding of the data sequence {1,0,1,0}: (a) OOK (b) Positive PAM (c) BPSK and (d) PPM.

equiprobable). The PSD for the OOK signal is then:

$$\Phi_{ss}(f) = \frac{1}{T}|P(f)|^2 + \frac{1}{T^2}\sum_{k=-\infty}^{\infty}\left|P\left(\frac{k}{T}\right)\right|^2 \delta\left(f - \frac{k}{T}\right) \quad (5)$$

In this equation we see that OOK results in discrete spectral lines in the PSD of the UWB signal.

Alternatively, we could use PAM with strictly positive values for the two pulse weights, so that $a_k \in \{\alpha_0, \alpha_1\}$ where $0 < \alpha_0 < \alpha_1$. and $\sigma_a^2 = (\alpha_0 - \alpha_1)^2/4$ and $\mu_a = (\alpha_0 + \alpha_1)/2$. Substituting these values in (4) we see that as with OOK, there are spectral lines present in the transmitted signal for positive-valued PAM and furthermore that the magnitude of the lines increases with the weight sequence mean. One advantage of the two schemes just discussed is that they only require that a single polarity of pulses be generated (although with two different amplitudes for the second case). Unfortunately, both OOK and positive PAM yield signals with spectral lines. In a system where transmit power must be constrained to meet limits on power spectral density, the presence of spectral lines may lead to reductions in total transmit power unless the lines can be reduced in some other way.

If instead we assume the ability to generate both polarities of the basic pulse shape, then we can use BPSK, where $a_k \in \{-1, 1\}$, so that $\sigma_a^2 = 1$ and $\mu_a = 0$. In this case, the PSD becomes simply

$$\Phi_{ss,BPSK}(f) = \frac{1}{T}|P(f)|^2 \quad (6)$$

Here we see that the spectral lines vanish because of the zero mean of the weight sequence. Figure 1 shows a sequence of pulses to illustrate each of the above techniques. In this figure, the gaps between pulses are relatively short for clarity. In systems reported in the literature, the inter-pulse space is long relative to the pulse width. Although not necessary, this is likely a limitation of early pulse generation technology [5].

B. Pulse-Position Modulation

The final modulation technique in the comparison, PPM, is fundamentally different from the PAM techniques described above because the pulses are not uniformly spaced in time. One form of PPM encodes the data bits in the pulse stream by advancing or delaying individual pulses in time relative to some reference. In this case, the equation for the UWB signal becomes

$$s(t) = \sum_{k=-\infty}^{\infty} p(t - t_k) = \sum_{k=-\infty}^{\infty} p(t - kT + a_k\beta T) \quad (7)$$

Here a_k correspond to the data where $a_k \in \{-1, 1\}$, and βT is the amount of pulse advance or delay in time relative to the reference (unmodulated) position. Deriving the PSD for (7) is more involved than for PAM. Although a general form for the signal above is unavailable, clearly such signals would have spectral lines. For example, if $\beta = 0.25$ then all pulses in (7) are advanced or delayed by $T/4$ so the signal is equivalent to an OOK signal with a correlated weight sequence that depends on the underlying data sequence. This signal has spectral lines, like OOK, and the same is true whenever $1/\beta$ is an integer greater than two. That the basic PPM scheme causes spectral lines is acknowledged in [2] when the authors discuss the use of time-hopping to mitigate the spectral lines caused by PPM.

In summary we see that spectral lines are present in the UWB signals for OOK, PPM and positive-valued PAM. For BPSK, the spectral lines can be made to vanish if the data sequence is assumed to be random and *i.i.d* with zero mean. There are also techniques that can help to reduce the effects of spectral lines, but the important point is that spectral properties will be a critical consideration for UWB signal design in order to achieve maximum power efficiency.

C. Comparison of Modulation Efficiency

We have already noted that because of the likely limits on UWB transmit PSD for wireless network applications, it will be important to select a power efficient modulation scheme with a smooth PSD. We can compare the efficiency of the techniques described above by determining the inter-symbol distance as a function of the bit energy, E_b. Figure 2 shows a simple representation of the symbol constellations for the each of the techniques. Here we assume that for the PPM system the time offsets for the pulses are chosen to make the two possible pulses orthogonal at the receiver, resulting in an orthogonal signaling scheme. Table I shows inter-symbol distances in terms of E_b for each technique which are computed using techniques in [7].

In these results we see significant differences between the modulation techniques. The PPM and OOK techniques are equally efficient and the positive PAM system is less so, but becomes the same in the limit as the the PAM becomes OOK. The BPSK techniques is antipodal signalling and has the greatest distance for equal bit energy. This difference provides a 3 dB advantage in efficiency: to achieve the same bit error rate

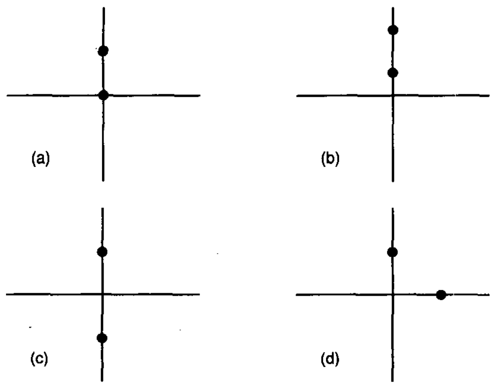

Fig. 2. Constellation diagrams for (a) OOK (b) Positive PAM (c) BPSK and (d) PPM.

(which is a function of distance) PPM or OOK must use 2× the bit energy, or 3 dB higher E_b.

D. Non-Coherent Demodulation Techniques for UWB

Non-coherent demodulation (an envelope detector), is often used to reduce complexity. Conventional narrowband systems use it, for example, to eliminate the need to acquire carrier frequency and phase before recovering symbol timing. UWB systems using OOK, PPM, and positive-valued PAM can use envelope detectors to simplify timing requirements and the bandwidth required of samplers or A/D converters, but at the expense of performance. UWB systems using BPSK must use coherent demodulation because every pulse would look the same out of an envelop detector. While this requirement might appear onerous, it is not. There is no need to recover a carrier frequency and phase separately from the symbol clock- in BPSK UWB they are one and the same, making the implementation simple. A major advantage of coherent detection is that true optimal coherent RAKE combining is available [7]. In non-coherent systems, it is not possible to combine individual multipath components to any advantage because their phase is unknown. This precludes the implementation of an effective rake receiver structure, since non-coherent combination of multipath components will not improve the signal-to-noise ratio.

The benefit of reduced complexity through a non-coherent design is limited by the fact that UWB already has many properties that reduce design complexity. A UWB receiver does not require carrier recovery or frequency translation and a UWB transmitter will potentially require no power amplifier. A discussion of implementation complexity issues can be found in [4].

Modulation Class	Example	Distance
Orthogonal Modulation	PPM	$d = \sqrt{2E_b}$
Amplitude Modulation	Positive PAM	$d < \sqrt{2E_b}$
	OOK	$d = \sqrt{2E_b}$
	BPSK	$d = 2\sqrt{E_b}$

TABLE I

E. Forward Error Correction for UWB Systems

Operation in a power-limited regime also has implications for forward error correction techniques. To complement the binary modulation techniques described above, low-rate binary codes, either binary convolutional or long block codes, are effective for improving error performance. These would provide additional coding gain relative to UWB techniques that use simple repetition coding to achieve processing gain. Many techniques are available to improve the performance coding of UWB systems, including soft-decision Viterbi decoding for convolutional codes, turbo codes, and concatenation with Reed-Solomon codes. Signal-space codes, such as trellis codes, that increase the alphabet size are good in bandwidth-limited applications, but are not as appropriate for UWB systems. More detailed discussion of coding techniques and their potential benefits can be found in [6], [7].

V. Summary and Conclusions

UWB technology has specific advantages that make it a good solution for indoor wireless network applications, including low transmit power, resistance to multipath interference and low implementation complexity.

Due to likely regulatory limits on transmit PSD, power efficiency is a critical issue for UWB systems. The choice of a modulation scheme affects a UWB system both through its inherent BER versus E_b/N_0 performance and though its effects on the PSD of the UWB signal. In particular, spectral lines could result in reduced performance by limiting total transmit power. BPSK is one solution that provides both good efficiency and spectral properties. Coding techniques appropriate for the power-limited regime also have the potential to significantly improve UWB system performance.

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