Range Extension for UWB Communications

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UWB shows great promise for use in a number of wireless communications applications, in particular, short range high bit rate networking. However, due to the emissions limits set by the FCC, commercial systems are limited in range for high data rates. To achieve greater range, both simple and advanced techniques need to be investigated. Current designs for UWB (at least those in the open literature) focus on a small number of modulation and pulse shaping schemes. As such, simple improvements should be investigated first to increase system range, such as better modulation schemes, channel coding, and/or Rake receivers. More sophisticated designs should then be investigated. In this white paper we investigate the use of different modulation and coding schemes on the Range of UWB, as well as a simple analysis of the Rake receiver. Additionally, due to the potentially large number of Rake fingers that may be needed, we discuss the need for low power Rake designs. Finally, we propose areas of research in UWB for communications.

Performance Tradeoffs for UWB

Commercial UWB systems must first meet the power and spectral requirements set by the FCC. Typically, UWB systems are impulsive, transmitting a pulse that lasts for a very short duration compared to the time between pulses. Indoor UWB wireless communication systems are limited in power spectral density by the FCC spectral mask This spectral mask has strong implications on the transmit power, pulse shape and pulse repetition pattern used in a UWB system.. The choice of pulse shape and pulse repetition is crucial to the performance of such systems, but these parameters are not discussed in this paper as they are currently being investigated. For the current analysis, it assumed that the spectrum is flat over the 3.1-10.6 GHz band and is limited to -41 dBm/MHz (meeting the FCC mask) and that the signal is sufficiently attenuated outside this band. Therefore, the maximum transmit power is assumed a constant here.

The received power can be modeled as proportional to the transmitted power by the relationship:

$$P_r = P_t - PL + G_t + G_r \quad \text{(dB)} \tag{2}$$

where PL is the path loss and G_t and G_r are the receiving and transmitting antenna gains, which are both assumed to be omnidirectional and have gains of 0 dBi. Clearly the antenna can play a crucial role in UWB performance, but we will save that for future investigation. The path loss for UWB signals is not currently well understood, but here, the standard narrowband path loss model will be used and is given by:

$$PL = 10n\log\left(\frac{4\pi d}{\lambda}\right) \tag{3}$$

where n is the path loss exponent, d is the distance from transmitter to receiver in meters, and λ is the wavelength corresponding to the center frequency of the signal.

It has often been proposed in the literature that a data symbol be repeated over several pulses to provide *processing gain*. The parameter N_s represents the number of pulses used to represent one data symbol. Therefore the effective bit rate, R_b can be given as:

$$R_b = \frac{PRF}{N_s} \log_2 M \tag{1}$$

where PRF is the pulse repetition frequency and the system employs an M-ary modulation scheme. (Note: in this analysis, the pulses are assumed to be transmitted at an *average* rate equal to PRF and are not necessarily transmitted at a regular interval. A time hopping system, similar to that described in [1], or other dithering methods may be employed).

The received power can also be expressed as:

$$P_r = E_b R_b \tag{4}$$

where E_b is the effective received energy per bit. For a given modulation and channel coding scheme, the BER is a function of E_b/N_o where N_o is the noise power spectral density. For a given receiver and assuming the system loading is constant[1], N_o will remain relatively constant, so the BER performance of the system will depend on how much energy per bit is captured by the receiver. Since, the transmit power is assumed to remain constant[2] (the maximum level), the received power at a given distance will also remain constant. Therefore, to change the received energy per bit to achieve a desired BER, the bit rate is the only available parameter that can change as seen in (4). For an impulse based UWB system, the bit rate can be changed by changing PRF or N_s. If PRF is changed, a corresponding change in the transmitted energy per pulse must be implemented to maintain a constant transmit power, but then there is no change in E_b. So to achieve a greater range for a given modulation and channel coding, the data rate must be reduced by spreading each data symbol over a larger number of pulses. (2), (3), and (4) can be combined and rearranged to give:

$$R_{b,\max} = \frac{1}{E_b} P_t \left(\frac{\lambda}{4\pi d} \right)^n \tag{5}$$

This shows the relationship between maximum achievable bit rate as a function of distance, assuming P_t, and E_b are constant (constant E_b for constant BER).

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[1] This is making a Gaussian assumption on the interference. It is not clear at this point how valid of an assumption that is.

[2] Clearly in a multiple access environment power control would be necessary and beneficial to system throughput. However, in this white paper we are concerned with extending the range of an individual link, so we examine the case of full transmit power.

Improving the Range of UWB

However, if a specific bit rate and BER performance are required, to increase range, the modulation, channel coding, and/or receiver design must be changed. In other words the required E_b/N_o at the receiver must be lowered. First, the effects of different modulation will be evaluated.

Effects of Modulation

For an impulsive UWB system, the data can modulate the transmitted pulses using pulse position modulation (PPM), bipolar signaling, pulse amplitude modulation (PAM), or on-off keying (OOK). (This is not necessarily a comprehensive list of possible modulation types but rather includes those that seem technically feasible given the state of the art). PPM and bipolar signaling will be evaluated here. [3] has shown that *M*-ary PAM has poorer performance than bipolar signaling (which can be viewed as 2-ary PAM). [2] shows that OOK has poorer BER performance than both binary PPM and bipolar signaling. The PPM time shift is assumed to be such that the signals are orthogonal. Depending on the pulse shape used, it may be possible to find a PPM time spacing better than the orthogonal case for binary PPM as in [1], but the pulse used for that analysis does not meet the FCC spectral mask assumed here. Therefore, no specific pulse shape is assumed here, just one that meets the FCC requirements. The PPM modulation is thus assumed to be orthogonal.

Transmit Power, P_t	595.7 µW	-2.2 dBm
Antenna Gains, $G_t = G_r$		0dB
EIRP (average)		-2.2 dBm
Path Loss		75.2 dB
Receive Power, P_r	18.30 pW	-77.4 dBm
Noise Power Spectral Density, N_o	$1.593\text{x}10^{-20}$ W/Hz	-198.0 dBW/Hz
Noise Power, P_n	11.95 nW	-69.2 dBm
Required E_b/N_o for BER < 10^{-3}		9.8 dB
Implementation Margin		2 dB
Energy per bit, E_b	$2.407\text{x}10^{-19}$ J	-186.2 dBW*s
Maximum Throughput, R_b	76.03 Mbps	

Table 1: Example Link Budget for binary PPM, range = 20 meters, free space path loss (n = 2)

The bandwidth is assumed to be 7.5 GHz (using the entire 3.1-10.6 GHz allowable band) and the carrier frequency for path loss calculation is assumed to be 6.85 GHz. The path loss exponent is taken as 2 for line-of-sight (LOS) conditions and 3 for non-LOS (NLOS) conditions. The average transmitted power is assumed to be -2.2 dBm:

$$P_{tave} = P_{sd}(BW) = 10^{(-41-30)/10}\,\frac{\text{W}}{\text{MHz}}\,7500\text{MHz} = 595.7\mu\text{W} = -2.2\text{ dBm}$$

A noise figure of 6 dB and an implementation margin of 2 dB are assumed. A target BER of 10^{-3} is used to find the necessary energy per bit required in an AWGN channel.

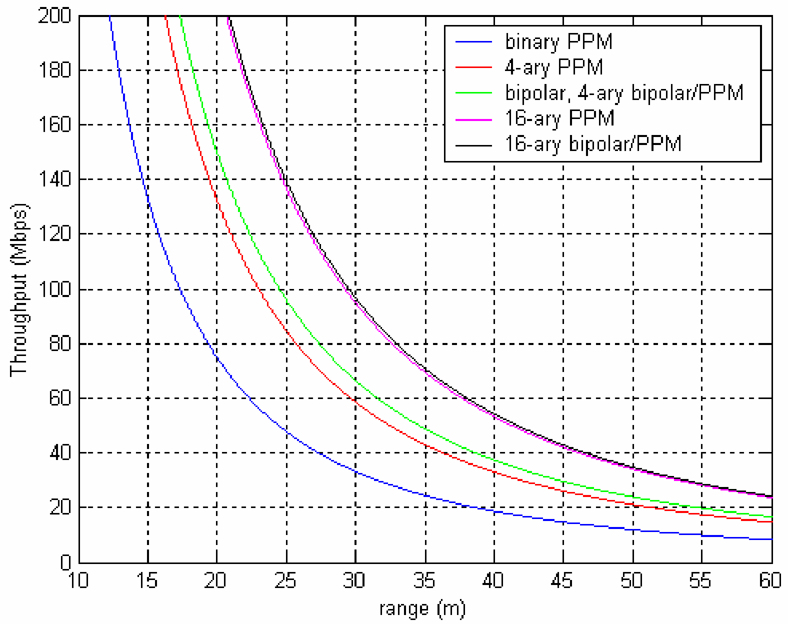

Figure 1: Maximum throughput for different UWB modulation types versus distance in an AWGN channel w/ LOS (n = 2)

The maximum achievable bit rate is plotted versus range for several different modulations in Figure 1 assuming a LOS component is present and in Figure 2 assuming a LOS component is not present. The PPM cases are all examples of *M*-ary orthogonal signaling. The bipolar signaling case is also plotted. Combinations of bipolar signaling with PPM, which are biorthogonal signaling, are also shown. For example, the 16-ary bipolar/PPM signal can take one 1 of 16 possible symbols with 1 of 2 possible polarities and 1 of 8 possible time positions. An example link budget is shown in Table 1.

In Figures 1 and 2, the best range performance is represented by the curves that are farther from the origin (giving the highest throughput for a given distance). It can be seen that higher order PPM offers improving performance over lower order PPM at the cost of higher complexity. Also higher order PPM will have an impact on the number of possible time-hopping codes for multiple access purposes. Bipolar signaling also offers significant improvement over binary PPM. Bipolar signaling combined with PPM offers better performance than just PPM for an *M*-ary system of each, although the gain of the combination over just PPM diminishes as *M* increases.

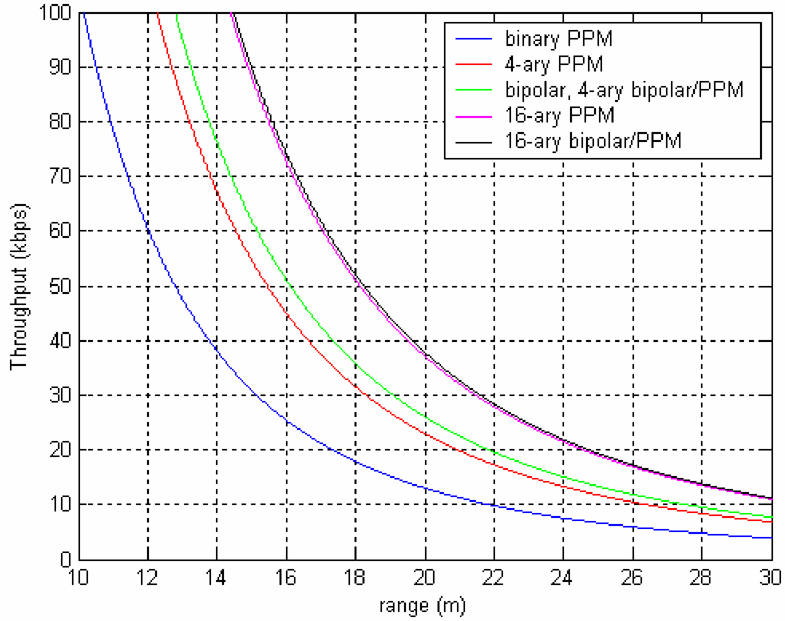

Figure 2: Maximum throughput for different UWB modulation types versus distance in an AWGN channel w/ NLOS (n = 3)

Effects of Channel Coding

A rate 1/2 constraint length 9 convolutional code was applied to the data before the binary PPM and bipolar modulation. The bits were decoded using Viterbi soft decoding. For a desired BER, the E_b/N_o required is much lower for the coded systems compared to the uncoded systems. Therefore, making the same assumptions as before, the range of a UWB system is improved when channel coding is added. Maximum throughput is again plotted as a function of distance comparing coded and uncoded systems in Figure 3 and Figure 4. In Figures 3 and 4, is seen that adding channel coding offers improved range performance. As the strength of the code used increases, it is expected that the range performance will also improve provided soft decision decoding is used.

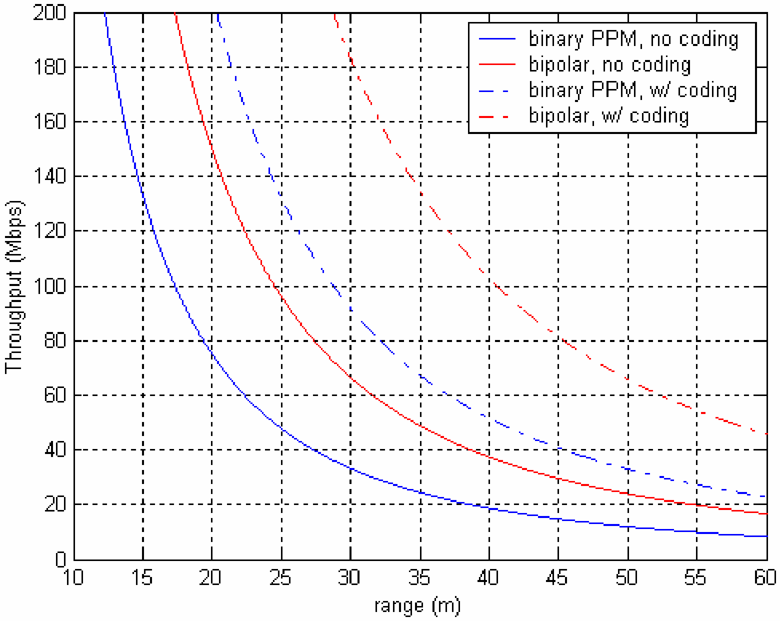

Figure 3: Maximum throughput for coded and uncoded UWB versus distance in an AWGN channel w/ LOS (n = 2)

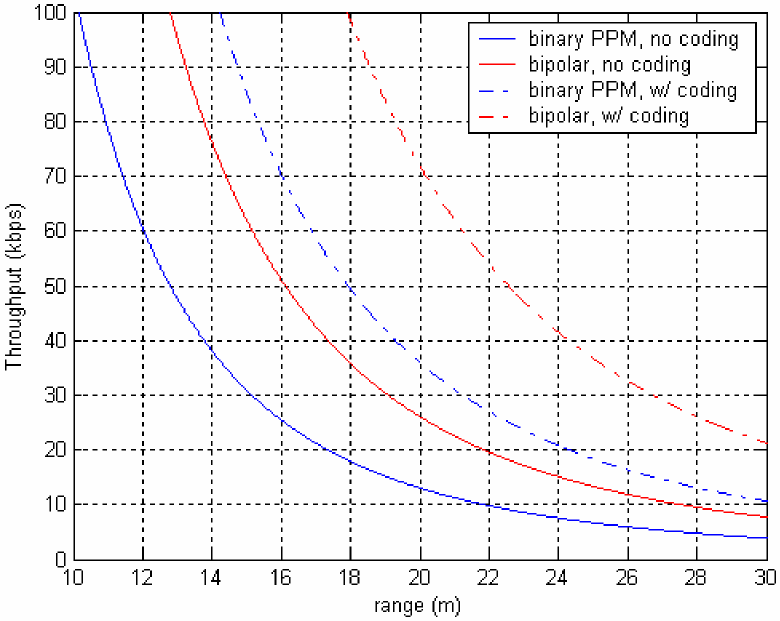

Figure 4: Maximum throughput for coded and uncoded UWB versus distance in an AWGN channel w/ NLOS (n = 3)

Effects of using a Rake Receiver

As UWB uses very short duration pulses for communication (on the order of nanoseconds), the multipath induced by the channel (typically of the order of 100s of nanoseconds) can be exploited using a Rake receiver to capture more of the energy of the transmitted signal and hence improve the range of the communication system. In the above scenarios, only the dominant component was captured by the receiver[3]. In the following model a Rake receiver containing up to 10 fingers has been used to examine the effect of the amount of energy captured by the receiver. The channel model used assumes that the resolvable multipaths have energies that follow a distribution that decays exponentially. As more energy is captured by using more fingers of the Rake receiver, the maximum range for a given throughput will increase. The ratios of energy captured and range with and without using a Rake receiver is given by:

$$E_{nfingers} / E_{1\,finger} = \left(d_{nfingers} / d_{1\,finger} \right)^n \qquad (6)$$

Figures 5 and 6 show the range versus throughput graphs for LOS and NLOS. As more of the energy is captured by using more fingers in the Rake, there is an improvement in range for a specific throughput.

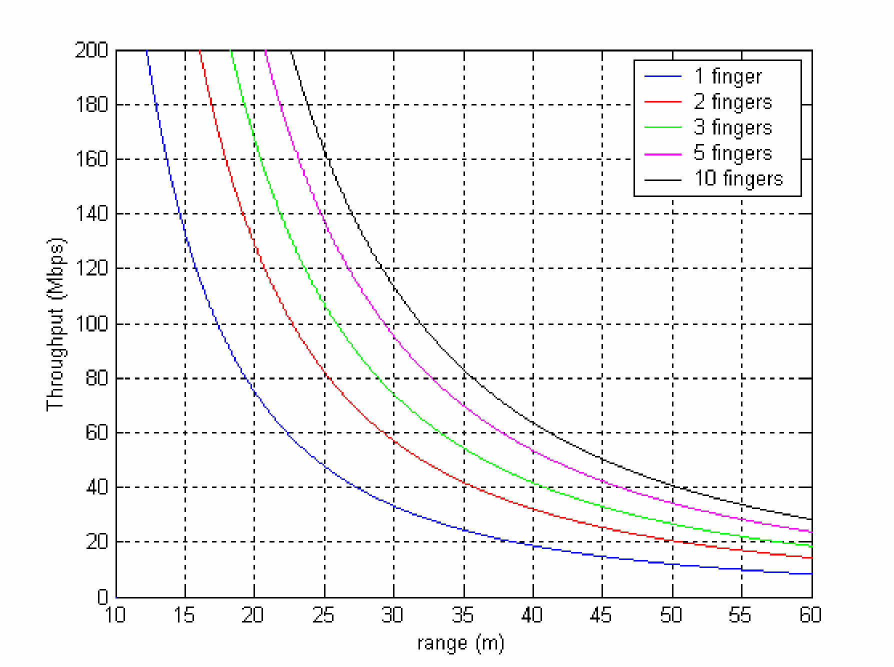

Figure 5. Effect of using a Rake Receiver with LOS $n = 2$.

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[3] In other words, we have assumed that by capturing the dominant finger we have captured enough energy to see path loss exponents of n=2 or 3. By using more fingers we assume that we will capture more energy. Another approach would be to assume that combining all possible fingers results in path loss exponents of n=2 or 3 and that anything less than all fingers results in a larger loss. In either case the Rake benefits should be similar.

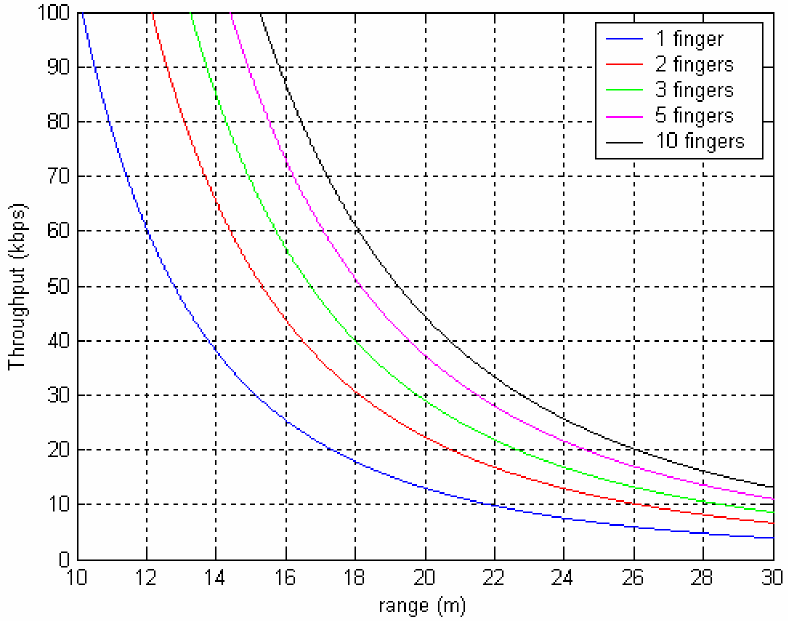

Figure 6. Effect of using a Rake Receiver with NLOS $n = 3$.

Rake Receiver Implementation Complexity

Clearly, Rake receivers will play a key role in UWB systems. However, a Rake receiver is complex in hardware and consumes a substantial amount of power. A spread spectrum Rake receiver has multiple fingers, and each finger consists of de-spreading blocks, correlators, code generators, compensators, de-skewers, and combiners. UWB Rake receivers will be similar. Several approaches have been proposed to reduce power dissipation of Rake receivers for handset modem chips such as a strength reduction transformation [4] and a look-ahead and relaxed look-ahead transformation [5].

We have investigated low-power design of Rake receivers targeting a third generation WCDMA (wideband code division multiple access) wireless system based on parallel operation of two code generators, an OVSF (orthogonal variable spreading factor) code generator and a scrambling code generator [6]. *The novel aspect of our design is a reduction of area as well as power dissipation without degrading the performance,* which is rarely achieved for most low-power designs. The parallel operation of the code generator eliminates the need for de-skewer blocks and enables the Rake receiver to share several blocks such as compensators, orthogonal variable code generators, and scrambling code generators. Hence, the proposed Rake receiver design reduces the circuit complexity and the power dissipation. In addition, the parallel operation enables the code generators and other blocks to operate at lower frequencies, which also contributes to the reduction in power dissipation.

We coded a conventional and the proposed Rake receivers in VHDL and synthesized the two Rake receivers targeting TSMC 0.18 μm CMOS technology with a supply voltage of 1.8 V. Both Rake receivers have four fingers. The power estimation was performed at the gate level under the spreading factor 8. The experimental results are shown in Table 1. The gate count in the table is the number of equivalent two-input NAND gates. As shown in the table, the proposed Rake receiver design reduces the total power dissipation by 55.2 % and the total gate count by 38.1 %.

Table 1 Performance of the Proposed Rake Receiver

	Power (μW)	Gate count
Conventional Rake receiver	1799.0	561 K
Proposed Rake Receiver	805.1	347 K
Savings	55.2 %	38.1 %

Early research indicates that we may have to consider a substantially larger number of multipaths, possibly as high as 20, for a UWB radio in the home networking environment in order to capture all of the available energy and increase UWB receiver range. This implies that the power dissipation of the Rake receiver as well as the circuit complexity is significant, and hence it is crucial to reduce both the power dissipation and circuit complexity for commercial applications of UWB radios. The proposed Rake receiver design is promising to achieve the two goals, which are often impossible for most low-power designs. We are interested in investigating the following topics.

First, our Rake receiver is a preliminary version aimed to validate and to estimate the efficiency of the proposed design. For example, the Rake receiver does not include the pilot channel and the time acquisition blocks, and the number of fingers is four. We propose to develop a complete Rake receiver that can be applied to UWB radios in the home networking environment. We can obtain the specifications of such a Rake receiver through the system level simulation of a UWB receiver/transmitter which are currently being developed. We will then implement the Rake receiver in VHDL incorporating the proposed design and investigate the efficiency of the proposed design in power and area. We believe that the reduction of power and area for the proposed design would be significant as the number of fingers is large for UWB radios.

Second, we will port the Rake receiver design to a TI DSP evaluation board and develop a co-processor using FPGAs, if necessary. Since the proposed Rake receiver design reduces the operating frequencies of various constituent blocks, the proposed receiver design will reduce the circuit complexity of the co-processor, if it does not eliminate the need for a co-processor entirely.

Third, we will prototype a UWB radio using the Rake receiver and other necessary components and demonstrate our UWB radio to achieve the desired data rate.

Other Potential Areas of Research

Most of the previously examined trade-offs represent fundamental communication design decisions. They provided some insight into the potential range improvements possible with current technology. However, there is clearly much more research that can be done in this field both fundamental as well as exotic. Examples of areas we are currently investigating include:

1) The effect of other pulse shapes and pulse repetition rates on the receiver range.
2) An AWGN channel has been assumed. Realistic channels will have some fading which needs to be estimated. As the number of multipaths increases, more estimation of the channel would be required. Correct estimation of the channel would directly impact the throughput of the system which would affect the range of the system. The sensitivity to channel estimation and robust channel estimation techniques both need to be investigated.
3) Currently only rate 1/2 codes have been examined for range improvement. Low rate codes can be examined due to the large spreading gains used in UWB communications. The effect of super-orthogonal and very low rate coding is currently being examined, as they might provide significant coding gains. Their coding gain could be exploited to improve the range of the system.
4) The UWB channel is not properly understood and the characterization of the channel would give a better idea of what channel characteristics could be exploited.
5) The effect of multiple users in the system needs to be examined. The modulation types that show the best performance in a single user case may not offer the best overall performance in a multi-user environment.
6) The large number of multipaths available mean that there may be a large amount of temporal diversity. This temporal diversity can be exploited to higher throughputs via MIMO coding techniques.

Conclusion

The use of UWB for communications is still in its infancy. Since one of the main application areas foreseen for UWB is short range high data rate communications, there is a need to investigate the impact of communication system design on the range. In this white paper we have examined some of the fundamental communications trade-offs which appear to be feasible for current UWB designs. Specifically, the effects of modulation, channel coding and Rake receivers were examined. Certain modulation types, being more energy efficient, were able to provide greater range performance for a given throughput. A system that employs channel coding was shown to improve the range performance over an uncoded system. Finally, the benefits of using a Rake receiver were illustrated when used in a multipath environment. Clearly, the design of low power

Rake receivers is an important area of research, and we briefly discussed some promising work in that area. Finally, we presented areas of research that we will examining in the near future to further improve UWB communication systems.

References

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