Design Challenges for Very High Data Rate UWB Systems

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Abstract

UWB is a promising radio technology for networks delivering extremely high data rates at short ranges. In this paper, different approaches to the physical layer system design for such networks are studied, and some of the challenges and opportunities inherent in their design and implementation are compared. For example, the use of extremely short duration pulses offers great possibilities for position location, but makes the timing synchronization task more complex. The ultra-wide bandwidth offers excellent frequency diversity and multipath resolution, but the channel estimation and multipath combining tasks are correspondingly more challenging. A pulse based UWB system (or impulse radio, IR-UWB) and a novel pulsed multicarrier UWB system are compared, emphasizing timing acquisition and performance in multipath. Some other differences, including interference avoidance, equalization, etc. are briefly dealt with.

1. Introduction

Considerable recent interest in ultra wideband (UWB) technology centers on its potential applicability for short-range, high-speed wireless communications. In general, there are many benefits to operating over a very wide bandwidth [1][2], one of which is the significant reduction of fading, since the short-impulse nature of the UWB waveform prevents a significant overlap of the signals. The ability to finely resolve individual multipath components at the receiver and "rake" in the energy of each can greatly boost the received signal-to-noise ratio, though this is achieved at the expense of increasing the receiver complexity. This same ability to finely resolve the multipath also leads to reduced signal energy per path, leading to increased channel estimation errors, which can counteract the advantage of the increased resolution. The overlay nature of UWB signals as regulated by the FCC dictates coexistence with other narrowband wireless communications as well as tolerance of the interference caused by them. Timing acquisition is another important consideration in system and receiver design, in terms of the preamble resources, as well as the receiver complexity devoted to it, respectively. Careful bandwidth selection of the UWB waveform can help balance the receiver complexity for capturing multipath energy while still benefiting from the reduced fading of the short duration pulses, and also enabling faster timing acquisition. In this paper we compare two different approaches to UWB system design – one based on "impulse" like UWB pulses, and the other a novel pulsed multicarrier UWB signal – with respect to these different tradeoffs.

The paper is organized as follows. In Section 2, the single user capacity of UWB systems in AWGN is computed and compared to that for some commonly considered unlicensed band alternatives. In Section 3, the channel model used as the basis of system design is briefly described. In Section 4 the two different UWB system designs mentioned above are described, and their different trade-offs compared. In the next two sections, two particular aspects of system and receiver design are examined in greater detail – timing acquisition requirements in Section 5 and multipath rake combining and equalizer requirements in Section 6. Section 7 presents some conclusions summarizing this study.

2. UWB capacity promises

In this section, we study the single user capacity of a UWB system in AWGN. From Shannon's formula for the capacity in b/s of a single user in AWGN [3] we have the following for the capacity of the UWB system occupying bandwidth *B*, as a function of the signal to noise ratio SNR at a distance *d* between the transmitter and receiver:

$$C(d) = B \log_2(1 + SNR(d)) \qquad (1)$$

The function *SNR(d)* represents the effect of path losses on the transmitted signal. The FCC R&O on UWB [10] allows for a UWB system bandwidth that extends from 3.1-10.6 GHz. The transmitted UWB signal is treated as having a constant p.s.d over this band set by Part 15 limits. It can be shown that the frequency dependent path loss is well approximated by considering the path loss at an effective "center frequency" given by the geometric mean of the lower and upper band edge frequencies. Thus, it follows that the received SNR at range *d* in AWGN is given by:

$$SNR(d) = -41.3-(-114)-6-20\log_{10}(4\pi f/c)-\gamma 10\log_{10}(d) \qquad (2)$$

Here, c is the speed of light, f is the effective center frequency mentioned above, γ is the exponent of path loss chosen according to the path loss model in [4], d is the distance to the receiver from the source, –41.3 dBm/MHz is the allowed emitted p.s.d per the FCC's R&O, -114 dBm/MHz is the standard thermal noise p.s.d. and a receiver noise figure of 6dB is assumed.

This UWB capacity is shown in Figure 1 as a function of the range. For comparison, the theoretical capacities in AWGN for some other unlicensed band WLAN systems are also shown. This figure shows the clear difference in range vs. rate tradeoffs for UWB systems compared to other unlicensed band systems that are regulated by limiting average power and bandwidth. It can be seen that UWB systems offer their greatest promise for very high data rates when the range < 10 m, approximately. It should be noted that these capacity results are very simplistic, since only AWGN is considered. It is necessary, e.g., to include the effect of multipath propagation, in order to quantify the true upper limit of the channel capacity for all the systems discussed here, but these figures provide the motivation for further investigations into applying UWB for high data rate, short range access.

3. UWB channel model

In order to implement an efficient UWB system for high-rate communications, it's critical to understand the characteristics of the propagation channel. A group at Intel R&D performed several channel measurements spanning the frequency spectrum from 2-8 GHz [5]. This database points out two important characteristics of an indoor environment for very high data rate UWB signals. First, the multipath spans several tens of nano-seconds in time, resulting in inter-symbol interference (ISI) for UWB pulses at high pulse repetition frequencies (PRF). Second, the very wide bandwidth of the transmitted UWB pulse results in the ability to individually resolve several multipath components, which will undergo less amplitude fluctuations (fading) since there will be fewer reflections that cause destructive/constructive interference within the resolution time of the received impulse.

A number of popular indoor channel models were evaluated to determine which model best fit the important characteristics that were measured and made available in [5]. Two important characteristics of the measurements and the model include (i) rms delay spreads from 5-25 ns, and (ii) mean number of significant paths from 20 to more than 100 for 0.167 ns path resolution time. The analysis and results of this channel modeling work have been submitted to the IEEE 802.15.3a channel modeling sub-committee [6] and is based upon a modified version of the Saleh-Valenzuela model [7]. A final channel model has been adopted by the 802.15.3a study group for the evaluation of PHY proposals [8].

4. UWB system designs

In this section, two different approaches to UWB signal design are briefly described and compared at a very high level – one design is impulse based, and another is based on a pulsed multicarrier approach. For example, an impulse based UWB system occupying a bandwidth ranging from 3-6 GHz generates a single pulse that spans this bandwidth and satisfies the requirements of the FCC spectral mask [10], and transmits this pulse at a PRF that satisfies the data rate as well as range requirements. Generation of such an impulse type of signal which spans multiple GHz bandwidth while efficiently "filling" the permitted area under the regulated spectral mask is challenging. In the time domain, too, the challenge is to ensure a proper pulse shape that minimizes ISI/ICI at high PRFs. An impulse based UWB system will have to engage some form of adaptive/fixed notch filters in order to mitigate the effect of interfering narrowband transmitters that it overlays. These notch filters will potentially create distortion of the received pulse shape that will cause losses due to ISI/ICI. In terms of scaling the design to higher data rates, some of the options available with an impulse based system are to increase the PRF or to choose higher order modulation. The former causes increased problems with ISI. The latter leads to higher peak to average power and increased linearity requirements on circuits. Direct sequence spread spectrum (DSSS) encoding offers another way to achieve data rate scaling through employing multiple parallel spreading codes. In this case the sequences need to be designed with proper autocorrelation and cross-correlation properties in mind [9]. DSSS techniques also enable sharing of the medium by uncoordinated networks.

The pulsed multicarrier UWB system is similar to an OFDM signal – it is based on multiple narrowband pulses that are "stacked" in the frequency domain to create an effective UWB pulse. The FCC R&O [10] specifies a minimum "instantaneous" bandwidth of 500 MHz, so that serves as a convenient unit of quantization in the frequency domain. The individual pulses can be systematically generated by generating different "carrier" frequencies as needed and modulating them with a common baseband pulse that has an approximate 500 MHz bandwidth. Thus, in one example, through appropriate choices of the carrier frequencies, 6 subbands are available to span the 3-6 GHz band. The signal design exploits the fact that UWB systems are inherently power spectral density limited, and so, to obtain the same peak power as the impulse based system with comparable bandwidth mentioned above, the PRF is approximately 6 times lower. This also allows the pulsed subbands to be transmitted in non-overlapping time intervals, thus significantly reducing the PAR problem common to multicarrier systems. The advantages of the lower PRF will be discussed later in Section 6. One feature of this signal design is that pulse shaping filters can largely be avoided, since the baseband pulse shape can be relatively easily chosen to provide compliance with the spectral mask regulatory requirements. The pulsed multicarrier signal design provides additional flexibility in dealing with narrowband interferers, such as 5 GHz WLAN systems that are overlaid, by possibly suppressing the carriers which specifically interfere with such signals. This can help avoid the use of notch filters, and provides a good way to achieve reasonable coexistence between multicarrier UWB systems and overlaid narrowband systems. There are different options for multiple access, based on time-frequency codes that can enable multiple networks to share a given spatial volume. Also, scaling the data rates can be achieved by varying the number of carriers employed in the system. This can also be used to differentiate low data rate/low complexity devices from high data rate devices. Finally, to address the issue of "regulatory" flexibility, as well as evolution with improving technological capabilities, it can be noted that the pulsed multicarrier system design can employ different sets of subbands that can be quite easily changed in response to these factors.

5. Timing acquisition

Fast timing acquisition and synchronization is an important requirement for high data rate packet wireless systems, since the preamble overhead (which is normally transmitted using a rate among the lowest data rates supported) needs to be minimized in order that overall throughput does not suffer. For example, for a 1024 byte packet being transmitted at 100 Mbps, a 10 μs PHY preamble amounts to an overhead of approximately 11%. At 500 Mbps, the same length for the PHY preamble amounts to about a 38% overhead, while at 1Gbps, the preamble will result in a 54% overhead. This is a simplistic calculation, and certainly the PHY layer preamble requirements can be affected by other aspects of the overall system design, however the point remains that short preamble length/fast acquisition is an extremely important factor in high data rate system design. In this section we compare the timing acquisition requirements for impulse based and multicarrier based UWB systems, in order to highlight the differences. For purposes of comparison, we consider a UWB bandwidth of 3-6GHz, and a 100Mbps data rate (uncoded), with a required $E_b/N_0 = 5dB$ in both cases. Also, the operating point on the receiver operating characteristic (ROC) needs to be specified – and this is accomplished by choosing the probability of false alarms $P_{fa}=1e\text{-}5$ and the probability of missed detection $P_{md} = 1e\text{-}5$ for this example.

For a single user in AWGN, the pulse matched filter followed by a sequence matched filter results in rapid acquisition of the preamble and pulse timing. However, for an impulse based UWB system which occupies the band from 3-6 GHz as in our example, a pulse matched filter is not practical, and a serial search correlator based approach is employed for timing acquisition. The range of the search for the serial correlator is the pulse repetition period (PRP), equal to $T_{s,p}= 10$ ns in this case. Examining the autocorrelation function of a typical pulse with this bandwidth, it can be determined that the timing increments for the serial search correlator during coarse acquisition are on the order of 0.08 ns. For the operating point on the receiver operating characteristic as specified above, for a impulse based system, the integration length in AWGN has been determined to be $N_p=11$ symbols. Combining all this information, we obtain the following for an estimate of the time required to search the entire 10 ns search range once:

$$T_{search,pulse} = (10/0.08)*N_p*10ns = 13.75\mu s \quad (3)$$

Next the multicarrier UWB system is considered with $L=6$ subbands occupying the band from 3-6 GHz. For this comparison, we consider a system that has a PRP of $T_{s,mc}= 6*T_{s,p} =60\ ns$ (i.e., 6 times longer compared to the impulse based system), and thus delivers an uncoded bit rate of 100 Mbps (=6*(1/ $T_{s,mc}$)). The detector used for such a system is quite different from that for the impulse UWB system considered above, as we can exploit the (relatively) narrowband nature of the individual subbands. As a consequence the autocorrelation function of the pulse has a larger time extent, and based on similar criteria as in the previous case, it was determined that the serial correlator search timing increments are on the order of 2 ns. Next, the detector used for the pulsed multicarrier system employs quadratic I-Q detection, and so for the ROC operating point considered above, the integration length required is $N_s=18$ symbols in the best case (energy is integrated from all 6 subbands). Combining all this, we obtain the following for an estimate of the time required to search the entire 60 ns search range once:

$$T_{search,mc} = (60/2)*N_s*10ns = 5.4\mu s \quad (4)$$

This is not the whole story, however. When the multipath channel model as described in Section 3 is considered, further differences are made apparent. For this study four sets of parameters for the channel model were selected, encompassing a range of LOS and NLOS environments, and 100 impulse response realizations were generated for each. For the impulse based system, the energy contained in the strongest path was computed as a fraction (denoted α_p) of the total energy in the impulse response for each of these realizations. A similar exercise was carried out for the pulsed multicarrier system, where 6 individual subband channel responses were generated for each of the above 400 channel realizations, and the fraction α_{mc} was computed for all 2400 impulse responses. In Figure 2 the cdf of α_p over the ensemble of realizations is shown, from which it was concluded that for over 95% of the multipath environments, the strongest path contained > 0.11 of the total energy. Figure 3 shows the corresponding plot of the cdf for α_{mc}, for the multicarrier UWB system. From this plot it was concluded that for 95% of the channel environments, the strongest path contained > 0.22 of the total energy. This supports the reasoning that the longer duration signaling pulses of the multicarrier UWB system already perform some energy integration, and thus the energy per pulse is greater than that in the impulse UWB system. For each system the inverse of the respective α is used to scale the search times in AWGN derived in (3) and (4) in order to obtain estimates for search time in multipath. This yields the following for acquisition time in multipath:

$T_{search,pulse} = (10/0.08)*N_p*10ns/0.11 = 125\mu s$

for the impulse based system, and

$T_{search,mc} = (60/2)*N_s*10ns/0.22 = 24.54\mu s$ for the pulsed multicarrier system (5)

Even if two parallel correlators were used for the impulse UWB system, in order to match the two correlators implicit in the I-Q detector for the pulsed multicarrier system, there is still a factor of 2.5 reduction in acquisition time for the multicarrier system. In both cases, multiple parallel correlators can be used to reduce the overall search time to a more desirable number such as 5-10 µs, but for a given complexity the multicarrier UWB system offers the possibility of faster timing acquisition compared to the impulse based system. As an example, in Figure 4 the CDF of acquisition time results are shown for an impulse based UWB system as in the example in this paper. Ten parallel correlators are employed and the effect of adopting different search strategies is shown. One interesting result is that dividing the search space into ten equal disjoint bins and assigining the ten correlators to linearly search through them individually yields the best performance, over all the other strategies, including a non-linear search strategy. It is also interesting to relate the result in (5) - which predicts an approximate acquisition time of 125/10 = 12.5 µs when using ten correlators - to the result in Figure 4, which shows acquisition times from 6-12 µs in the worst case. The lower number in the actual simulation is probably due to optimized search strategy, among other reasons.

One final point to note about the multicarrier UWB system is that because of the narrowband nature of the individual subbands, it is in fact feasible to design digital matched filter based approaches to timing acquisition which may further reduce the acquisition times.

6. Rake and channel equalization requirements

The channel measurement studies performed to date and the channel model from Section 3 indicate two primary challenges for UWB signal detection at high data rates. First, the fine time resolution (approximately equal to pulse duration T_d) implies that the transmitted symbol energy is distributed among a large number of multipath components. This means that some form of energy combining (rake) is needed for reliable detection. Second, from [6] the typical rms delay spreads (~20 ns), are comparable to the symbol duration for the impulse based UWB system in the example from Section 4 (which has a symbol duration of 10ns). Hence, the resulting ISI will span several symbol durations. The rake combiner will contribute to some mitigation of this ISI, but for small number of rake taps, post rake combining symbol equalization may be necessary. For a DSSS UWB system, the spreading code will likewise mitigate the ISI, however the ICI caused due to the pulse shape will lead to some loss of processing gain. For the multicarrier UWB system of our example from Section 4, the symbol duration or the PRP is 6 times larger (60 ns), and so the ISI and consequent equalization requirements are much milder, similar to OFDM vs. single carrier systems. The multicarrier UWB system, however, may need additional adjacent channel interference suppression in multipath.

To consider the issue of rake complexity, note that for a given multipath delay spread T_m and pulse duration T_d, the number of resolved channel coefficients $K = T_m / T_d$ will increase as the UWB bandwidth increases. The cost of rake combining will grow proportionally, and this will become important in determining overall implementation cost / complexity.

Based on the channel model as described in Section 3, it is possible to analyse the output SIR of the rake receiver as a function of the number of taps. For the impulse based system, some results were reported in [11] and these can be compared to similar results for a multicarrier system. To summarize the results, it is found that the number of rake taps needed to achieve a given rake output SIR is approximately ten times as large for the impulse UWB system when compared to that for the multicarrier system of the example considered in the previous section.

Thus, on both counts, we find that the multicarrier system can be expected to have lower receiver complexity that the impulse based system based upon smaller rake and equalizer requirements.

7. Conclusion

In this paper, some of the key issues surrounding the design of high data rate UWB systems have been examined, and different system designs for UWB systems are compared – an impulse based UWB system and a novel multicarrier UWB system. It is seen that the multicarrier system has many interesting features. It offers additional degrees of freedom that can be exploited to help with some of the difficult tradeoffs that one is faced with in an impulse based UWB design for high data rate systems, such as rake receiver and equalizer complexity, timing acquisition complexity, narrowband interference suppression/avoidance, etc. Currently, research is underway in some of these areas, as well as in the area of efficient silicon implementations.

8. References

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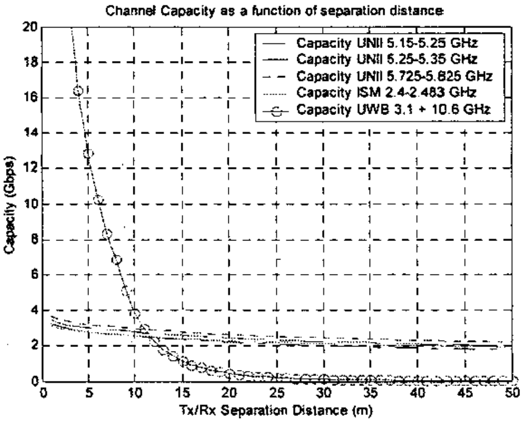

Figure 1: Theoretical capacity of unlicensed systems in AWGN

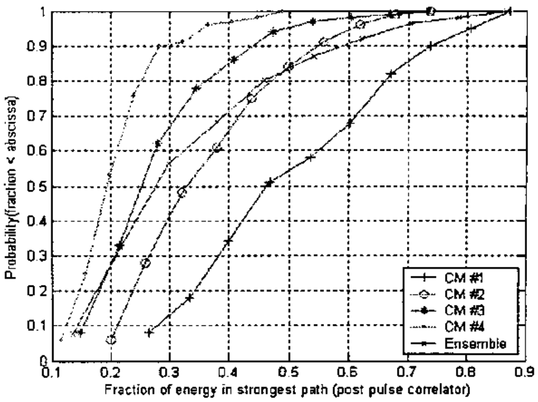

Figure 2: CDF of fractional energy in strongest multipath component for a 3 GHz impulse based UWB system

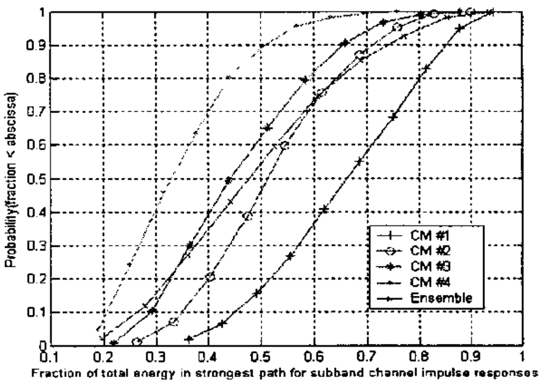

Figure 3: CDF of fractional energy in strongest subband multipath component for a 3 GHz multicarrier UWB system.

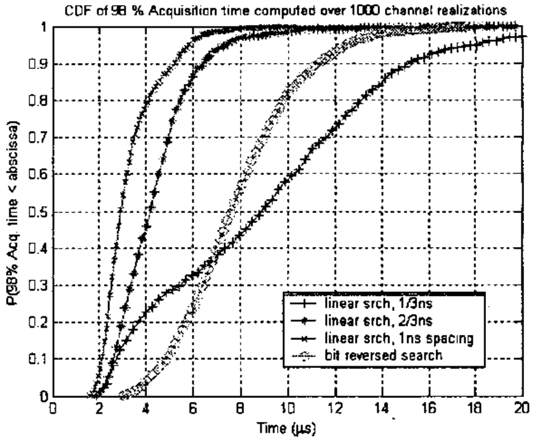

Figure 4: CDF of acquisition times for an impulse based UWB system using 10 parallel correlators and different search strategies.