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Pulse Sense: A Method to Detect a Busy Medium in Pulse-Based Ultra Wideband (UWB) Networks

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Abstract – **This paper proposes a new MAC scheme for pulse-based UWB ad hoc networks. The proposed scheme provides distributed medium access through pulse sense, which is similar to carrier sense in narrowband systems, and it is suitable for low power applications with light traffic. The key idea of the pulse sense mechanism is to examine spectral power components of the received signal, which avoids searching for narrow pulses in the time domain. Simulations show that the proposed pulse sense method achieves high probability of detection with low probability of false alarm. Further, the pulse sense circuit detects pulses in a short time, is moderate in hardware complexity, and is insensitive to timing jitter, interference, and varying channel conditions.**

Key Words– **UWB, carrier sense, pulse sense, low data rate, ad hoc networks, sensor networks**

I. INTRODUCTION

UWB (ultra wideband) communication provides many advantages over traditional narrowband communication such as high data rate, low probability of detection and intercept, robustness for multipaths, and low power dissipation. Two different UWB communication systems – carrierless, pulse-based systems and carrier-based systems – have been pursued recently. A pulse-based UWB system has several advantages over carrier-based systems including simple hardware (and hence low power dissipation) and robustness to multipaths and interference. Hence, pulse-based systems are more suitable for low cost, low power applications [1], [2].

Existing MAC (medium access control) for UWB systems targets heavy traffic volume and relies on time division multiple access (TDMA) and time hopping [3]-[6]. A centralized TDMA approach such as the one employed in the IEEE 802.15.3a MAC is a good strategy for a system with heavy traffic, since a UWB device may dissipate more power receiving than transmitting. TDMA allows devices to sleep and save power when not involved in a transaction [3]. However, in networks with light traffic and many nodes, the centralized control traffic significantly increases the amount of overhead bits, thus wasting energy and reducing the useful network lifetime. Time hopping allows distributive medium access and is suitable for a dynamic network topology [4]-[6]. However, random code selection does not guarantee optimum orthogonality. Further, time hopping systems are susceptible to the multipath interference of other users. Time hopping systems that solve these issues incur a large overhead penalty in hardware complexity [4]-[6]. Therefore, TDMA and time hopping are not suitable for low cost, low power applications with light traffic, such as sensor networks.

We propose a MAC based on pulse sense for pulse-based UWB systems. Pulse sense detects a busy medium in the presence of UWB traffic just as carrier sense detects signals in a certain frequency band. The proposed pulse sense circuit detects the presence of pulses in a short time period in various channel conditions, and it is moderate in circuit complexity. The main advantage of a MAC based on pulse sense is that it provides distributed, random access to the medium without the overhead of control packets.

The paper is organized as follows. Section 2 reviews preliminaries. Section 3 presents the proposed pulse sense architecture and discusses design alternatives and issues. Section 4 presents simulation results for the proposed pulse sense scheme, and Section 5 summarizes the paper.

II. PRELIMINARIES

This section reviews several existing methods for detecting the presence of UWB pulses and the shortcomings of these methods. Next, it describes the target application scenarios for our pulse sense method. Finally, it reviews our earlier UWB receiver architecture, into which our proposed pulse sense block is integrated.

A. Existing Methods for Pulse Detection

A peak detector is a simple method, which holds the peak value of the signals received within some time period. Since the UWB receiver operates over a wide bandwidth, a peak detector is incapable of separating a UWB signal from a narrowband signal. This is a problem since UWB is meant to coexist with narrowband devices. Furthermore, the peak detector is susceptible to noise spikes.

A matched filter does not require synchronization to detect the signal energy [7]. However, an analog matched filter is not adaptable to dynamic channel conditions and is complex in hardware. To sample the received signal, a digital matched filter requires a fast ADC with wide dynamic range, which dissipates a large amount of power. Further, a digital matched filter requires a large number of taps to handle the dense multipath environment of pulse-based UWB.

Correlation with a sliding window can also be used to detect low duty cycle UWB pulses [7]. A serial correlation, which is low in circuit complexity, results in a long sensing time, so it is unsuitable for pulse sensing. Multipath spreading complicates the sliding correlation by spreading the signal power over a longer period of time. Parallel correlation improves acquisition speed but at the cost of high circuit complexity.

An interleaved periodic correlation processing (IPCP) pulse detection system operates by correlating the received signal with samples of itself delayed by one pulse repetition interval (PRI) [8]. IPCP is mostly useful for detecting homogenous radar signals in the absence of inter symbol interference (ISI), co-channel interference, and modulation, which all produce differences between successive symbols. These differences cause the received signal to be less correlated with a delayed version of itself, which degrades the performance. Additionally, timing jitter causes further degradation due to the long integration period and sharp correlation peak.

Sections 3 and 4 demonstrate the robustness of our pulse sense method to the weaknesses of these existing schemes.

B. Application Scenarios

Applications suitable to pulse-based UWB include sensor networks, RFID, or tracking people and assets. The upcoming IEEE 802.15.4a standard targets such applications and emphasizes light traffic volume, low power, and location awareness over throughput. Pulse-based UWB is of particular interest for the above applications since it offers location and communications capabilities with low power dissipation.

The baseband nature of a pulse-based system allows simple hardware implementation with no intermediate mixers or down conversion stages. Further, pulse-based UWB signals result in many resolvable multipaths, so they are robust to the harsh multipath environments likely for sensor networks. The low duty cycle allows multiple simultaneous transmissions in a densely packed network and also maintains low average power that significantly reduces interference to narrowband systems [9]. The ranging capability of UWB is a tremendous advantage for low-power devices that previously relied on GPS. To this end, pulse-based systems are suitable for low power location and radar applications [9]-[11].

Pulse sense provides two important (and required) services for a distributed, random access MAC such as the CSMA MAC in IEEE 802.15.4. One service is to detect an incoming packet and the other is to ensure that the channel is free before transmitting. Pulse sense provides these services without synchronization and demodulation of special control packets. Further, a distributed, random access MAC avoids the centralized control and single point of failure in TDMA, and it avoids the complex receiver of time hopping. It is also more suited to large, dense networks and allows spatial reuse [12]. Moreover, for sensor network protocols with long sleep cycles, the pulse sense MAC allows data transmissions to begin immediately upon wake-up without wasting overhead on decoding control packets or re-establishing a piconet [13].

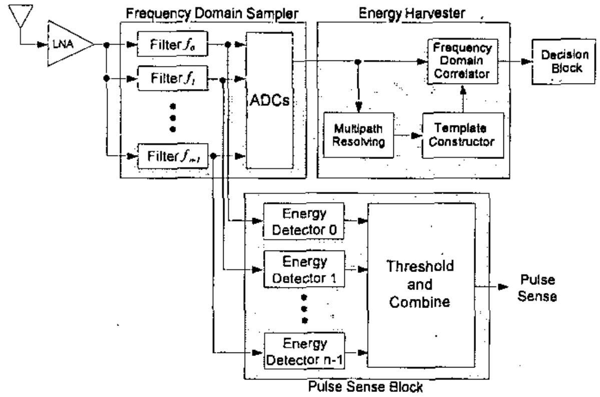


Figure 1: UWB Receiver with a Pulse Sense Block

C. Frequency Domain Receiver for Pulse-Based UWB

As an early work, we investigated a new architecture for pulse-based UWB receivers employing the frequency domain approach [14]. The key idea for the architecture is to extract the frequency components of the received signal and to perform signal processing in the frequency domain to increase the effective sampling rate. The upper blocks in Figure 1 show the receiver architecture, which consists of a wideband low-noise amplifier (LNA), a frequency domain sampler, an energy harvester, and a decision block.

The frequency domain sampler consists of a filter bank followed by multiple ADCs. The narrowband filters are passive LC bandpass filters with the second order transfer function $1/\left(s^2+(k\omega_o)^2\right)$. A filter captures an in-band spectral component of the received signal at frequency f_i, where $f_i = kF_0$ for an integer k. The fundamental frequency F_0 is determined by an observation period T_p such that $F_0=1/T_p$. Next, the ADC captures spectral samples at the pulse repetition rate, which is much lower than the Nyquist over-sampling rate to save power as well as circuit complexity. The energy harvester performs baseband signal processing such as the correlation and rake operations in the frequency domain, which results in efficient hardware.

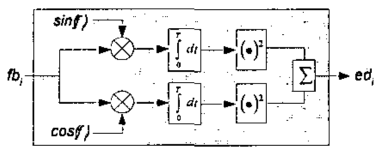
III. Proposed Pulse Sense Architecture

The key idea of the pulse sense mechanism is based on the duality property between UWB and narrowband systems. A narrowband signal modulated on a carrier is spread over a large window in the time domain, which is sensed as in carrier sensing. For a UWB signal, the spectral power components are spread over a large spectrum, whereas its time domain signal is concentrated on a narrow pulse. Therefore, our pulse sense scheme examines spectral power components to avoid searching for a signal in the time domain. The bottom block in Figure 1 shows the overall architecture for our proposed pulse sense block, and we discuss the sub-blocks next.

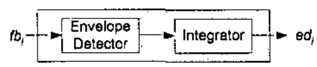
A. Energy Detectors

The energy detectors of the pulse sense block detect the spectral power components of UWB pulses. Each energy detector receives a frequency component, fb_i, which is an integer multiple of the pulse repetition frequency (PRF) and F_0. Pulse activity at the PRF causes the filters to oscillate.

Figure 2 (a) shows a maximum likelihood detector for a signal of unknown phase at frequency f_i. The fb_i signal is from a filter bank, and the sine and cosine terms are the basis functions. The remaining blocks compute and combine the energy at frequency f_i. Since a maximum likelihood detector is relatively complex requiring mixers and oscillators, it may not be power efficient. An alternative circuit is an envelope detector followed by an integrator as shown in Figure 2 (b).



(a) Maximum Likelihood Energy Detector



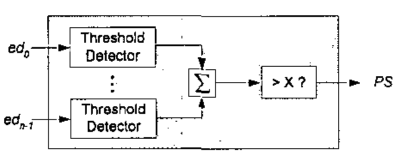
(b) Envelope Detector

Figure 2: Energy Detectors

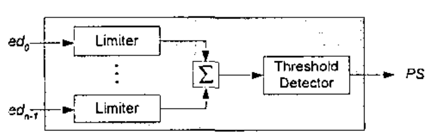
B. Combination and Threshold

The spectral power components captured by energy detectors must be combined to detect the presence of UWB pulses, while rejecting narrowband signals. To this end, we ensure that the majority of spectral components match the low power footprint of a UWB signal. We consider two possible methods of combining the spectral power components called *hard combination* and *soft combination* as shown in Figure 3.

Figure 3 (a) shows the hard combination scheme. The filter outputs are applied to threshold detectors, which generate binary values. If the sum of binary values exceeds a threshold X, then a pulse is detected. This operation is robust to a strong narrowband interferer, as high energy in one frequency band will not exceed the threshold X. Since the threshold detectors produce binary values, the sum and comparator blocks may be implemented efficiently with digital circuits.



(a) Hard Combination



(b) Soft Combination

Figure 3: Combination and Threshold Block

Figure 3 (b) shows the soft combination scheme. The outputs of the energy detectors pass through limiters, so a strong narrowband interferer does not dictate the final decision. The analog limiter outputs are summed and then compared to a threshold. The soft combination is resilient to frequency selective fading, as the soft decision gives more weight to strong spectral components. Soft combination requires only one threshold detector, but the limiter and adder circuits are analog to avoid ADCs at the detector input.

C. Sensing Period

A pulse sense circuit should have a short sensing period (the IEEE 802.15.4 MAC specifies an 8 symbol maximum) and report a high detection probability P_d and low false alarm probability P_{fa}. The time limit is necessary to prevent the pulse sense block from reporting stale, useless information, as well as to reduce the power dissipation.

In the presence of a pulse train, the filters of our frequency domain receiver reach their maximum amplitude well within one PRI [14]. Considering that a practical sensing period is up to 8 PRIs, the filters operate well within the practical time limit. Next, when the maximum likelihood energy detector in Figure 3 (a) is employed, we need to set the time periods for the multiplication and integration. A longer period harvests more energy to result in an increased detection probability P_d and a decreased false alarm probability P_{fa}. However, the longer period also increases power dissipation. A similar tradeoff exists for integration in the threshold detector in Figure 3 (b). Finally, the number of "looks" refers to the number of times the pulse sense block performs the combination and threshold operations. Increasing the number looks increases detection probability P_d and decreases false alarm probability P_{fa} at the expense of longer sensing period and greater power dissipation.

In summary, the system needs to choose a suitable sensing period and number of looks considering the trade-offs among sensing time, power dissipation, P_d, and P_{fa}.

IV. SIMULATION RESULTS

We modeled a system level receiver with a pulse sense block as shown in Figure 1. There are 7 filter banks and the center frequencies are f_0 = 4 GHz, f_1 = 5GHz, ..., f_6 = 10 GHz. The PRI is 5 ns to result in a pulse rate of 200 MHz, and a rate ½ code results in a 100 Mbps data rate with BPSK. We considered the Intel channel models CM1 (line-of-sight) and CM4 (extreme non-line-of-sight) [15]. Note that the 5 ns PRI can incur significant ISI since the RMS delay spread can be up to 25 ns for CM4. We vary the E_b/N_0 from 12 dB to 20 dB, which corresponds to link distances from 10 m to 4 m for an 11 dB noise figure at the antenna terminal. The receiver can demodulate the coded data with a BER of approximately 2×10^{-4} at the worst-case E_b/N_0 of 12 dB in CM4.

Figures 4 and 5 demonstrate the proof-of-concept for the proposed pulse sense scheme. Figure 4 shows performance

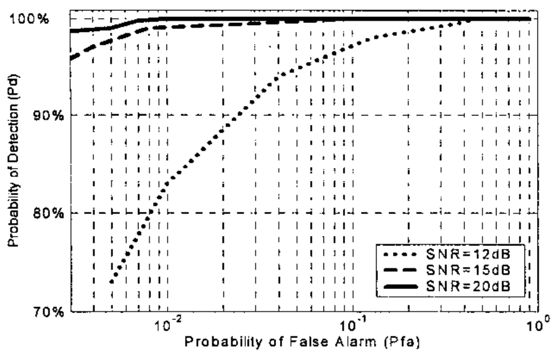


Figure 4: P_d vs. P_{fa} for AWGN

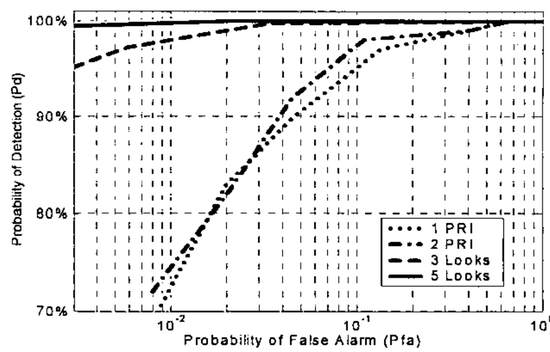


Figure 6: P_d vs. P_{fa} with Additional Sensing Time, CM4, SNR = 12 dB

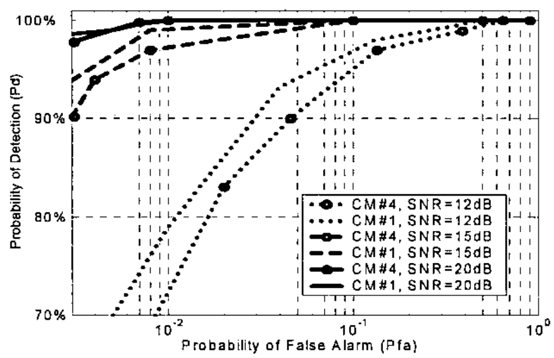


Figure 5: P_d vs. P_{fa} for CM1 and CM4

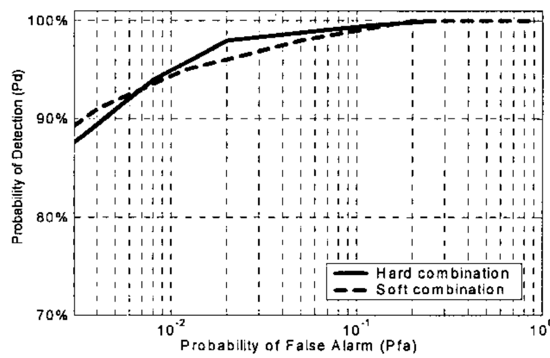


Figure 7: P_d vs. P_{fa} with Strong Narrowband Interferer, CM1, SNR = 15dB

in AWGN, which matches statistical noise theory [16]. Figure 5 shows the performance under the multipath conditions of CM1 and CM4. The energy detector is the envelope detector in Figure 3 (b) since the maximum likelihood detector of Figure 3 (a) does not result in significantly better performance. The energy detector uses the soft combination method and takes one look at the filter bank outputs and integrates for a half-bit period of 1 PRI = $20/f_0$.

Note that the addition of the channel model does not significantly degrade performance from AWGN. This is because the pulse sense circuit considers the total spectral energy in the channel, so spreading the total energy over the multipaths does not significantly affect performance. This is a considerable advantage in the harsh multipath environment of UWB. Pulse sense performs slightly better in CM1 than CM4, and this is because CM4 may contain multipaths with a large gain as compared to the first path. These multipaths contribute to spectral power at frequencies other than f_i, so there is some loss in the spectral energy at each f_i.

For low power applications, a high P_d is more important than a low P_{fa}. A high P_d reduces collisions, and collisions require retransmission of the entire packet, which at least doubles the energy required to send the data. A low P_{fa} decreases latency, which is not usually a concern for low power applications with light traffic such as sensor networks.

From Figures 4 and 5, the pulse sense scheme as described above is practical in all channel conditions for distances less than 6 m (E_b/N_0 = 15 dB). For greater distances, the pulse sense circuit can lengthen its sensing time to significantly improve performance as described below.

In Figure 6, we show that detection probability P_d and false alarm probability P_{fa} can be improved with additional sensing time. Figure 6 considers the worst-case channel model of CM4 and SNR of 12 dB. We look at time both in terms of the number of periods of f_0 and in terms of the number of looks. We first extend the listening time from 1·PRI to 2·PRI for one look. Then, for a listening time of 1·PRI, we extend the number of looks to 3 and 5; we base the decision on the result of 2 out of 3 or 3 out of 5 looks. Both schemes increase P_d while decreasing P_{fa} at the cost of longer detection time. Note that increasing the number of looks improves performance much more significantly than lengthening the listening time. This is likely a result of the long baseline listening time as compared to $1/f_0$ and suggests that the listening time can be reduced to save power.

Next, Figure 7 presents the performance of the soft combination and the hard combination circuit in the presence of a strong narrowband interferer. The narrowband interferer's power level is such that the UWB signal to narrowband interference ratio is −10 dB, and the interferer is placed in the 5.1 GHz ISM band so that it will cause activity in filter f_1. The multipath channel model is CM1 and the SNR is 15 dB. The hard decision block requires 4 of the 7 spectral components to be present, and the threshold levels are ideal for each P_{fa}. The soft decision block also considers ideal threshold levels, and the limiters have a maximum output of 1.8 dB above the average UWB signal level.

In Figure 7, the hard combination method performs best when the P_{fa} is relatively high, whereas the soft combination method performs best when the P_{fa} is relatively low. The crossover point is around $P_{fa} = 5\times10^{-3}$. Therefore, for low power applications, the hard combination method is preferable to maximize P_d and avoid retransmissions.

The reason that hard combination performs best for high P_{fa} is that the threshold value is low, so the narrowband signal may add up to 1.8 dB of energy into the soft combination block, depending on the threshold value. This energy alone may be enough to trigger false alarms and has the effect of moving the curves in Figure 5 to the right. However, for the hard combination, the narrowband energy does not add any extra energy to the hard combination block, since the block receives binary input values.

At low P_{fa} the threshold value is high, so the narrowband signal cannot add as much energy to the soft combination block. Thus, soft combination yields a better decision. However, at low P_{fa}, the hard combination block continues to weight all inputs – including the interferer – equally, so it does not perform as well as the soft combination block.

Finally, we consider the effects of timing jitter. The jitter has a uniform, random distribution in the range of a few picoseconds, which is enough to significantly lower the narrow correlation peak of an IPCP detector in multipath conditions. For pulse sense, the performance with jitter shows no visible difference from the performance without jitter as shown in Figures 4 and 5. This is because the small timing jitter only slightly moves the location of the spectral power components, and the filters capture approximately the same amount of energy as for the case with no jitter.

V. Conclusion

Existing MAC schemes for pulse-based UWB systems are intended for applications with a heavy traffic volume and rely on TDMA and time hopping [3]-[7]. However, both TDMA and time hopping methods are inefficient for large, low cost, low power networks with light traffic volume, such as sensor networks. We proposed a new MAC scheme for pulse-based UWB systems targeting low cost, low power applications with light traffic volume. Our MAC scheme is based on random access and pulse sense to provide distributed medium access. The proposed pulse sense scheme detects a busy medium in the presence of UWB traffic just as carrier sense detects signals in a certain frequency band. The key idea of the proposed pulse sense scheme is to examine spectral power components of the received signal, which avoids searching for a signal in the time domain.

Simulations of the proposed pulse sense system show that it can achieve high probability of detection with low probability of false alarm even in harsh channel conditions. Narrowband interferers do not significantly degrade performance, so a pulse sense system can coexist with narrowband systems. The proposed pulse sense circuit has several advantages including short detection time of pulses, moderate hardware complexity and insensitivity to timing jitter, and it is compatible with the IEEE 802.15.4 MAC requirement of detecting a signal within eight symbols.

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