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A RAKE Receiver Employing Maximal Ratio Combining (MRC) Without Channel Estimation for UWB Communications

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Abstract - An alternative method to channel estimation is presented as a means of supplying a RAKE receiver with the coefficients for Maximal Ratio Combining (MRC). The proposed RAKE receiver utilizes Time-Hopping Pulse Position Modulation (TH-PPM), and is specifically designed to be used in Ultra Wideband (UWB) communication systems in which channel estimation becomes problematic because of the high sampling rate required. The MRC coefficients are determined by a simple process of averaging the received energy for a given correlator finger over the course of a pilot sequence of *P* pulses. Performance of the proposed RAKE receiver is investigated through simulation using a discrete-time implementation of the multi-path channel model published by the IEEE 802.15.3 task group. The proposed RAKE receiver's Bit-Error-Rate (BER) performance is compared against other RAKE receivers relying on channel estimation.

I. INTRODUCTION

With the recent Federal Communications Commission (FCC) Ultra Wideband (UWB) emissions mask released in 2002 [1], there has been a surge interest in UWB technologies. Traditional UWB technology relies on sub-nanosecond pulses that have a corresponding signal bandwidth greater than 500 MHz [2]. Referred to as Impulse Radio, IR-UWB technology offers the possibility of developing high data-rate, low power-consumption communication systems that provide greater immunity to multi-path fading due to the pulse's fine delay resolution [3], and greater Bit-Error Rate (BER) performance at a given Signal-to-Noise Ratio (SNR) due to the signal's spreading in spectrum [4]. Pulse Position Modulation (PPM) and Pulse Amplitude Modulation (PAM) are the two modulation schemes generally used in IR-UWB, and are often used in conjunction with a pseudorandom (PN) code implemented either by performing time dithering on the pulses (TH-UWB) or though a Direct-Sequence Spread Spectrum (DS-SS) approach [2]. In this paper, a TH-UWB scheme is assumed, but the results would still apply to IR-UWB systems in general.

Within a multi-path environment the transmitted UWB pulse appears at the receiver as a collection of attenuated and delayed replicas of the original pulse, assuming the frequency selectivity of the channel is ignored. A RAKE receiver, made up of a set of *N* correlators, each delayed in time to correspond to a given multi-path component or pulse replica, is usually employed in multi-path channels because it allows a greater percentage of the signal energy to be collected for the purpose of symbol estimation [5]. A number of different methods have been proposed for combining the output of the correlators in RAKE receivers, but for single-user systems, it has been found that Maximal Ratio Combining (MRC) results in the best performance [2]. The MRC coefficients correspond to the relative amplitudes of the pulse replicas received by each correlator finger, such that more emphasis is placed on stronger multi-path components and less on weaker ones when the output of the correlators is summed for the symbol decision. In a typical RAKE Receiver, the MRC coefficients are provided by performing channel estimation.

Numerous approaches to channel estimation in UWB communication systems have been suggested, but there are significant drawbacks associated with the implementation of each of them. A maximum-likelihood (ML) approach would provide optimal performance, and could be used for both data-aided estimation, in which a pilot sequence of *N* symbols known *a prior* is transmitted and received, and also for nondata-aided estimation in which no pilot sequence is present [6]. However, the complexity and required sampling rate required to implement such an approach in a physical device is prohibitive [7]. Other suboptimal estimation approaches include the sliding window (SW) and successive cancellation (SC) algorithms used in Direct-Sequence Code Division Multiple Access (DS-CDMA) systems [7], as well as a least-squares method that assumes equally delayed multi-path components [8]. While these channel estimation approaches require less computation, they still require sampling at unrealistically high rates. Simulations for the SW and SC algorithm approaches and the least-squares method used sampling frequencies of 20 GHz and 10 GHz, respectively [7]-[8]. Current CMOS technology is simply not capable of producing the high frequency clocked comparators needed to construct the required ADC, and even given the existence of such high frequency ADCs, the hundreds of milliwatts of power they would consume would run counter to the low power design criteria set by most UWB communication system designers [9]. Schemes do existing for relaxing the demands upon the ADC. The given pilot signal used for channel estimation could be sent multiple times, and given that the ADC were delayed with each new transmission of the pilot signal, the sampled points could be interleaved to achieve the required sampling rate [10]. The drawback to this approach is the greatly extended pilot sequence duration. Multiple ADCs could also be used, interleaved within either the time or frequency domains to reduce the burden upon any one ADC [9]. While this scheme does mitigate the need for a single high frequency ADC, collectively the ADCs still consume too much power. In general, these issues regarding the sampling frequency are an inherent aspect of UWB, given that the spectrum allocated for such signals is from 3.1 GHz to 10.6 GHz. To sample at or above the Nyquist rate becomes problematic given the large bandwidth of the UWB signals themselves.

The proposed solution to the problems that arise from the overtaxing sampling requirements for channel estimation is to simply do away with channel estimation altogether. The purpose of this paper is to present a novel, reduced-complexity RAKE receiver that still utilizes MRC to weight correlator outputs before combining them for the symbol decision, but without the use of channel estimation. The alternative to channel estimation used in the proposed Reduced Complexity RAKE (RC-Rake) is to average the energy received for each given correlator finger during a pilot sequence of M symbols. Furthermore, by delaying the input to the correlators by during the course of the pilot sequence, it becomes possible to “scan” for a greater number of high amplitude multi-path components with a small set of correlator fingers.

The remainder of the paper is organized in the following manner: Section II provides an account of the TH-UWB modulation scheme used with the RC-Rake, while section III introduces the IEEE 802.15.3 channel model used later in the simulations of the RC-Rake communications system. Section IV provides a discussion of the RC-Rake and also briefly describes the All-RAKE (ARake), Selective-RAKE (SRake), and Partial-RAKE (PRake), which are commonly found in the literature [2],[3],[4],[11]. Last, section V presents the results of the simulations used to compare the BER of the proposed RC-Rake against those RAKE receivers listed above.

II. SIGNAL FORMAT

The transmitted signal modulated using TH-PPM is given by the expression:

$$s(t) = \sqrt{E_p} \sum_{i=-\infty}^{\infty} p(t - iT_{FP} - c_i T_{CP} - b_i T_{PPM}) \qquad (1)$$

Here, *p(t)* is a second order derivative Gaussian pulse of unit energy, and E_p is the energy of a single pulse. The second derivative Gaussian pulse is widely used in UWB research because its frequency spectrum satisfactorily meets the

FCC emission masks [2]. T_{FP} is the frame period such that $f_{FP} = 1/T_{FP}$ corresponds to the frequency at which pulses are transmitted. Generally, the Gaussian pulse duration is fractions of a nanosecond, whereas T_{FP} is generally on the order of 50 ns to 100 ns, such that the transmitted signal has an extremely low duty-cycle. T_{CP} is the duration of the chip period used for the time dithering, and c_i is the given value of the TH code, in which $0 \le c_i \le N_{TH}$, where N_{TH} is the cardinality of the TH code. T_{PPM} *is the* time delay used for the pulse position modulation, and b_i is the given bit in the binary sequence to be transmitted. Figure 1 depicts a modulated signal for a single bit of binary value 0. The Gaussian pulse duration is 0.5 ns, as is T_{PPM}. T_{CP} is 1 ns, and the cardinality of the TH code, N_{TH}, is 5. For the pulse shown in Figure 1, the value of c_i is 1. It should be noted that Figure 1 does not display the entire frame period, but merely the first 5 ns of the 60 ns frame. The longer frame period is used to ensure that no inter-symbol interference (ISI) is present in the received signal.

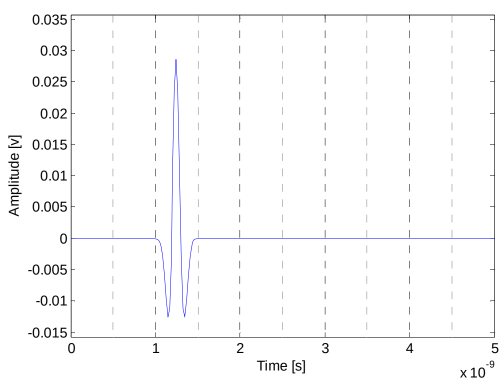

Figure 1. Gaussian Pulse with TH-PPM Modulation

IEEE CHANNEL MODEL

The IEEE 802.15.SG3a sub-committee released a UWB channel model in 2003 that was developed after considering the findings of numerous researchers working within the area of UWB [2],[12]. The model is based on experimental results that suggest the multi-path components arrive in clusters, and that the arrival time of the clusters and the arrival time of the multi-path components within the clusters can be modeled with Poisson random variables [2]. Furthermore, the amplitudes of the first multi-path components of each of the clusters can be modeled with a log-normal random variable; the amplitudes of each of the multi-path components within each cluster can be modeled by a second log-normal random variable; and the phase of each multi-path component can be assumed to be either 0°or 180° with equal probability [2]. The sub-committee also released suggested parameter values for the cluster and multi-path component average arrival rates, the cluster and multi-path component power decay factors, the cluster and multi-path component coefficient fluctuation standard deviations, and the overall channel amplitude gain standard deviation [2]. Given these suggested parameters, the IEEE channel model can be applied to four different scenarios that depend on the distance between the transmitter and receiver, and whether the channel is Line-of-Sight (LOS) or Non-Line-of-Sight (NLOS) [1]. Table 1 lists the four scenarios accounted for by the IEEE sub-committee suggested parameters.

Table 1. IEEE UWB Channel Model Scenarios

Scenario:	Distance (m):	LOS/NLOS
A	0-4	LOS
B	0-4	NLOS
C	4-10	NLOS
D	>10	NLOS

Figures 2 and 3 depict the discrete channel impulse response under scenarios A and D respectively. The two figures clearly show that at shorter distances there are fewer multi-path components, but that the multi-path components display larger amplitudes, while at longer distances there are more multi-path components, but with much smaller amplitudes. Furthermore, the root mean square (rms) delay spread of the channel impulse response under scenario D is significantly larger then the rms delay spread of the channel impulse response under scenario A.

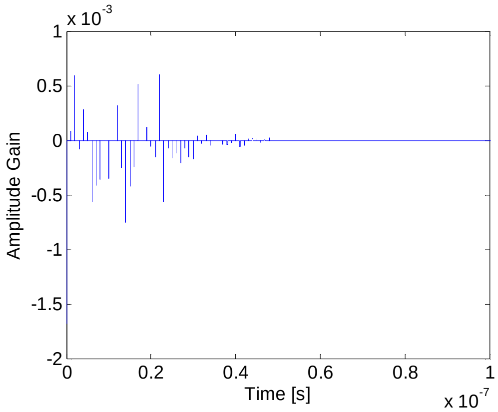

Figure 2. Discrete Channel Impulse Response under Scenario A

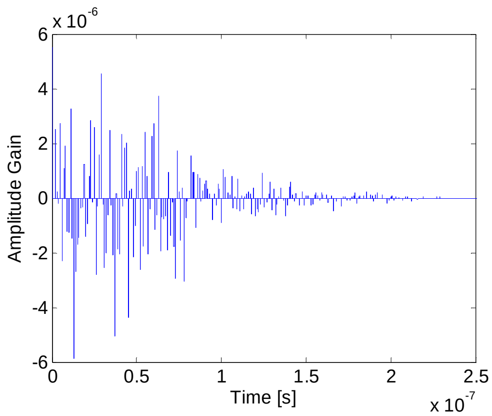

Figure 3. Discrete Channel Impulse Response under Scenario D

III. THE RC-RAKE

A standard RAKE receiver structure with N parallel correlators is depicted in Figure 4.

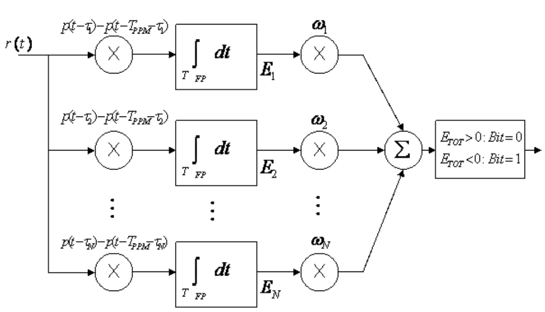

Figure 4. RAKE Receiver Structure [2]

Each correlator finger consists of a mask that is mixed with the received signal and an integrator, the output of which is the energy collected by the given correlator finger over the course of the frame period T_{FP}. Each correlator mask is generated by subtracting a Gaussian pulse waveform shifted by the PPM delay from a Gaussian pulse wave without the PPM delay. The entire mask is then shifted in time by τ_N, which is set to correspond to the arrival time of a given multi-path component of the received signal. The time delay due to the time dithering applied at the signal transceiver must also be accounted for, but is ignored in this discussion for the sake of simplicity. The energy collected from each correlator finger is then multiplied by a weighting parameter, ω_N, and summed with the other weighted correlator finger outputs before the symbol decision is made. The purpose of the weighting parameters is to place more emphasis on those correlator fingers with the better SNR when making the symbol decision. Maximal Ratio Combining (MRC) refers to when the weighting factors are determined such that they correspond to the relative amplitudes of the given multi-path components.

In a traditional RAKE receiver design the $\{\tau, \omega\}$ parameters for each given correlator finger are supplied by additional hardware that performs channel estimation by sampling the received signal either during a pilot sequence transmission, or during data transmission itself. However, as discussed in section I, all of the methods that might be used to implement channel estimation have serious drawbacks when applied to UWB.

The RC-Rake proposed here avoids using channel estimation. Instead, the τ_N parameters are forced to be a multiple of given delay value, T_d, such that for any given correlator n:

$$\tau_n = kT_d \qquad 0 \le k \le M_{PATH} \qquad (2)$$

where k is an integer and M_{PATH} is the maximum number of multi-path components the receiver considers. As a result, the correlator fingers can only be locked on to pulse replicas that arrive at delay times of set intervals. However, this tap delay, T_d, can be set to be a fraction of the Gaussian pulse duration, allowing the receiver to reliably account for most multi-path components and even multi-path component interference. The weighting parameters, ω_N, are then determined during the transmission of a pilot sequence, which is known to the receiver *a priori*. For pulse *p* in a pilot sequence, *s(p)*, with *P* total pulses, the τ_n parameter for the *n*th correlator finger is given by:

$$\tau_{n,p} = (pn(\mathrm{mod}\, M_{PATH})) \times T_d \qquad (3)$$

Essentially, during the pilot sequence, the correlator fingers "scan" for the multi-path components that arrive at intervals of T_d. Even a small number of correlator fingers can scan over a large number of multi-path component arrival times given that the pilot sequence is long enough. For any given time delay parameter τ_n, the corresponding weighting factor, ω_n, is then given by:

$$\omega_n = \sum_{p=1}^{P} E_{n,s(p)}\Big|_{s(p)=0} - \sum_{p=1}^{P} E_{n,s(p)}\Big|_{s(p)=1} \qquad (4)$$

Here $E_{n,s(p)}$ refers to the energy collected by the *n*th correlator finger (with the time delay parameter τ_n) for the *p*th pulse in the pilot sequence, *s(p)*, given that the *p*th pulse corresponds to either a binary 1 or 0. Essentially, during the pilot sequence, on each occasion at which a correlator finger is set to a given value of τ_n, the output of the correlator finger is either added to or subtracted from the value of ω_n, depending on whether the output agrees or disagrees with the known value of the transmitted bit. Given that *P* is the number of pulses in the pilot sequence, M_{PATH} is the number of multi-path components considered by the receiver, and *N* is the number of correlator fingers in the receiver design, a given weighting parameter, ω_n, will be the summation of the correlator finger outputs on $R = \frac{PN}{M_{PATH}}$ separate occasions. For larger values of R, the energy collected by the correlator fingers due to Additive White Gaussian Noise (AWGN) and not the multi-path component of the transmitted pulse is averaged out. As a result the ω_n parameters become a more reliable estimate of the multi-path component energy collected by a correlator finger when delayed by the given τ_N parameters. Given that the energy of a pulse is interpreted as the energy delivered by a voltage source feeding a 1Ω resistor, and the IEEE channel is assumed to be non-frequency selective (therefore each pulse replica varies only in gain and delay but not pulse shape), the relative energies of each multi-path component is comparable to the relative amplitudes of the multi-path components. The weighting coefficients are therefore determined in MRC fashion, although without the use of channel estimation. After the transmission of the pilot sequence, the *N* largest ω_n parameters are selected and those $\{\tau_N, \omega_n\}$ parameters are used with the received data pulses.

The three RAKE receivers that are generally discussed in the literature—the ARake (Adaptive Rake), SRake (Selective Rake), and PRake (Practical-Rake) —all rely on channel estimation to determine the $\{\tau_N, \omega_N\}$ parameters. The ARake has a correlator finger for each multi-path component in the received pulse, and is used only as a theoretical benchmark, as such a receiver would be too complex to implement [11]. The SRake relies on channel estimation to determine the *N* best multi-path components for a receiver with *N* correlator fingers [4]. While more practical than the ARake, the SRake receiver is still forced to monitor each of the multi-path components to determine those that are the strongest [2]. The PRake is the most practical, using channel estimation to determine only the first *N* multi-path components for a receiver with *N* correlator fingers, but of course shows poorer performance [11]. Theses RAKE receivers were used in the simulations discussed in the next section as a means by which to assess the performance of the RC-Rake.

IV. SIMULATION RESULTS

The RC-Rake performance was investigated by performing Matlab simulations. As a reference point for comparison, the ARake, SRake and PRake where also simulated. For the simulations, discrete channel responses were used to simplify the requisite calculations. With the discrete-channel response, a bin duration of 1 ns was used, and all multi-path components arriving within the given bin period were combined together. Given that discrete-channel responses were used, perfect channel estimation was assumed for the ARake, SRake, and PRake. Also, the RC-Rake tap delay was set equal to the bin duration. Simulations were run for each of the four possible scenarios under the IEEE channel model. For each of the four RAKE receivers under each scenario, ten different channel instantiations were simulated with 10,000 pulses transmitted for each channel instantiation. The parameter settings for the simulations were as follows:

Sampling Frequency: 50 GHz
Frame Period, T_{FP}: 60 ns
Chip Period, T_{CP}: 1 ns
TH Code Length: 2000 bits
TH Code Cardinlity, N_{TH} : 5
Pulse Duration: 0.5 ns
PPM Delay, T_{PPM} : 0.5 ns
Transmitter Power: -30 dBm
RC-Rake Tap-Delay, T_d: 1 ns
RC-Rake Max Path, M_{PATH} : 25
RC-Rake Pilot Sequence Length, P: 500

Figures 5 through 8 depict the BER versus the received signal SNR for all four RAKEs under the four different IEEE channel mode scenarios, A through D respectively. Under all four scenarios, the RC-RAKE performance is only slightly poorer than that of the SRake, which is to be expected, given that the RC-Rake finds the 5 best multi-paths of the first 25, while the SRake finds the 5 best multi-paths of all the possible multi-paths. As the channel impulse responses in Figures 2 and 3 show, the 5 best multi-path components are generally within the first 25, but not always.

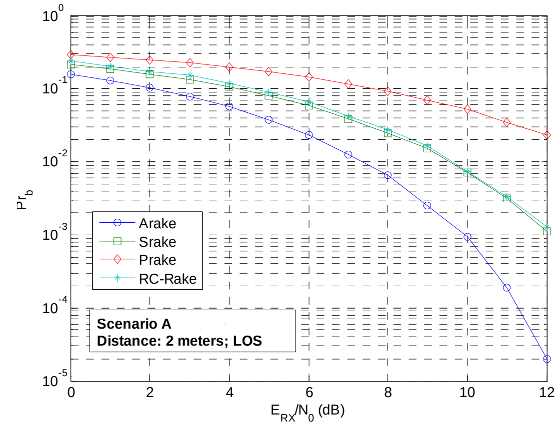

Figure 5. RAKE Performance under Scenario A

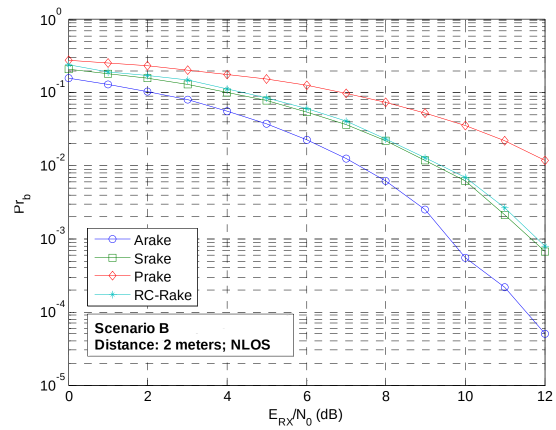

Figure 6. RAKE Performance under Scenario B

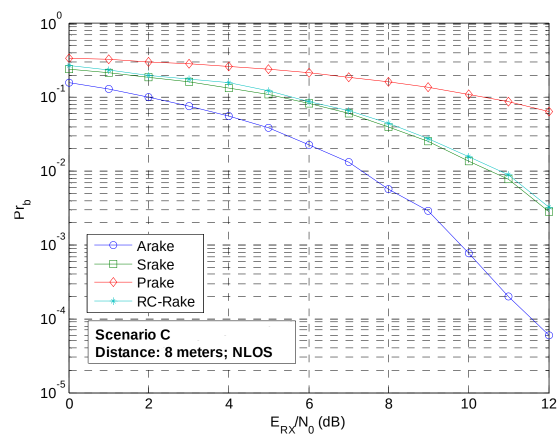

Figure 7. RAKE Performance under Scenario C

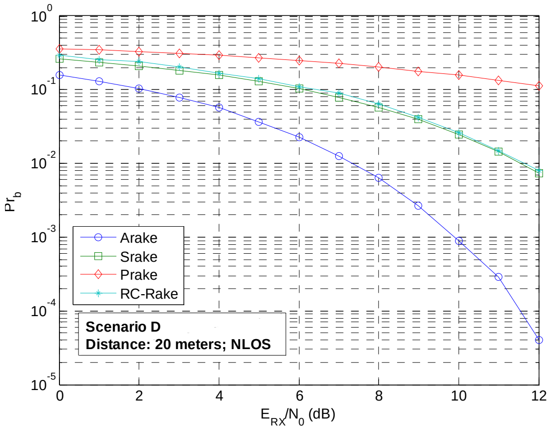

Figure 8. RAKE Performance under Scenario D

VI. CONCLUSION

Given that P is the number of pulses in the pilot sequence and M_{PATH} is the number of multi-path components considered by the receiver. These two parameters have an affect on the performance of the RC-Rake. As in the simulation of this paper the RC-Rake pilot sequence length was set at 500 pulses, and the M_{PATH} parameter was set at 25. The simulations performance shows that the proposed RC-Rake outperforms the PRake, and performs nearly as well as the SRake under all of the IEEE channel model scenarios without channel estimation.

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