Acquisition of Direct-Sequence Ultra-Wideband Signals

Iyappan Ramachandran, Sumit Roy*
Department of Electrical Engineering
University of Washington
Seattle, WA 98105
Email: {iyappan, roy}@ee.washington.edu
*Contact author: Tel/FAX: (206) 221-5261/543-3842

***Abstract*— Very high rate packet data systems such as those based on ultra-wideband (UWB) signaling face an increasingly important challenge - achieving fast timing acquisition and synchronization (which must be done typically on an individual packet basis) to minimize preamble overhead and optimize (packet) throughput. Impulse based UWB modulation schemes use short (nano-second) time-duration pulses that are appropriately shaped - the resulting high resolution in time implies that the acquisition algorithm must employ sub-pulse duration steps, thereby leading to a large search space if a serial timing acquisition approach is used. Moreover, owing to the strict average transmit power limitations on UWB transmissions resulting from the Part 15 limits imposed by the FCC, a large number of pulses need to be integrated for reliable acquisition decisions, which consequently leads to large mean acquisition times (MAT). In this paper, we investigate the performance of the conventional serial search and random search schemes applied to the acquisition of UWB signals in multipath environments. It is shown that over typical UWB multipath channels, a random search scheme may yield lower MAT than serial search.**

I. Introduction

Ultra-Wideband (UWB) modulation [1], [2] is the basis for wireless personal area networks (WPAN) within IEEE 802.15.3a standards group intended for use in the 3-10 GHz band on an unlicensed basis in U. S. subject to the Part 15 rules that specify a maximum transmit power spectral density of -41.3 dBm/MHz. Despite the strict limits on average transmit power, UWB schemes can achieve very high aggregate data rates over short distances due to the very large bandwidths employed [3]. In a multipath dominated environment, such large transmission bandwidths allow for fine time resolution of multipath arrivals, which implies reduced fading per resolved path [4] compared to narrow(er) bandwidth modulation.

Historically, impulse (or narrow pulse) modulation has been used to generate such large transmission bandwidths (order of GHz) along with careful shaping of the modulating pulse shape. While several other UWB modulation approaches have been presented in the literature [5], [6], [7], in this work we focus exclusively on a Direct Sequence UWB (DS-UWB) scheme which in principle is very similar to a standard DS-SS modulation; this is embodied in a proposal before the 15.3a standard body [8]. In contrast to the raised cosine shaped pulses transmitted at 1.368 Gcps used in [8], we use a baseband pulse shaped as the 2^{nd} derivative of a Gaussian pulse transmitted at 1 Gcps to achieve the necessary spectral control. Our pulse duration is determined so that there is negligible inter-chip-interference at this chip rate. Typically, UWB systems use short codes of length 16 or 32 to achieve code division multiple access (one period of which constitutes a data symbol) resulting in symbol rates of 62 or 31 Msps.

Such narrow pulse widths imply that acquisition algorithms should employ correspondingly narrow step sizes which could lead to potentially large search spaces. The low transmission power spectral density further indicates a need to integrate several pulses for reliable decisions, which also increases the mean acquisition times. However, the fine time resolution results in a (very) large number of significant resolved multipath components, which indicates a potential for it's judicious exploitation to reduce the acquisition times. In summary, design of acquisition schemes for UWB systems have significant differences from those for conventional wideband systems and accordingly require new analytical approaches.

Initial development and analysis of acquisition schemes ([9] and [10], for example) were made with the assumption that there exists only one resolvable path and consequently only one H_1 cell (in-phase cell). The analysis of the effect of the presence of multiple H_1 cells on the performance of a serial correlator has been investigated in [11] and [12], where it has been assumed that the number of in-phase cells (H_1 cells) is negligibly smaller than the total number of cells that an acquisition receiver has to test, which is characteristic of wideband DS-SS systems using long PN codes. This assumption has allowed the authors to lump all the H_1 cells in to a *single equivalent* H_1 cell with an appropriate probability of detection; this reduces the analysis of acquisition in multipath to the familiar one with a single H_1 cell. Owing to the use of short codes and the presence of a large number of multipath components, such an assumption is not justified for the analysis of acquisition of UWB signals. In this paper, we provide a *new* analysis for the mean acquisition time of conventional serial search *without the above assumption*.

The fine time resolution of UWB signals and the strict power limitations imposed by the FCC [13] call for innovative ways of acquisition that will result in lower acquisition times. One such acquisition scheme that holds considerable promise is the random search scheme, in which the step size of the acquisition receiver is chosen randomly. To the authors' knowledge, acquisition using random search has not been treated analytically in literature, except in [14], where only the 'ideal' case of zero false alarm and unit detection probability is considered. We analyze the acquisition scheme using random search and derive a compact formula for the mean acquisition time for a general scenario.

The rest of the paper is organized as follows. In Section II, the UWB signal model and the channel models under consideration are described. In Section III, we describe the structures and algorithms of the acquisition systems considered in this work. Section IV contains performance analyses of the acquisition systems leading to numerical evaluation of the mean acquisition times and Section V concludes the paper.

II. System Model

A. Signal model

For this work, DS-UWB signaling with bi-phase (BPSK) modulation is assumed. For data transmission, each bit is sent modulated by a length N_c PN sequence of ± 1 binary chips that are periodically repeated in each bit interval, just as in conventional DS-SS systems with short spreading codes. However during the preamble-assisted acquisition phase, it is assumed that an unmodulated PN sequence is transmitted. The UWB signal chosen is a baseband pulse shape given by the 2^{nd} derivative of a Gaussian pulse [14].

$$p(t) = \sqrt{\frac{4}{3t_n\sqrt{\pi}}}\left(1-\left(\frac{t}{t_n}\right)^2\right)\exp\left(-\frac{1}{2}\left(\frac{t}{t_n}\right)^2\right) \quad (1)$$

The parameter t_n determines the effective time width of the pulse T_p and hence its bandwidth. The auto-correlation of the pulse $p(t)$ is

$$R_p(\tau) = \left(1-\left(\frac{\tau}{t_n}\right)^2+\frac{1}{12}\left(\frac{\tau}{t_n}\right)^4\right)\exp\left(-\frac{1}{4}\left(\frac{\tau}{t_n}\right)^2\right) \quad (2)$$

The energy in the pulse $p(t)$ is unity and the signal transmitted with energy E_c per chip is thus given by

$$s(t) = \sqrt{E_c}\sum_k c_k p(t-kT_c) \quad (3)$$

where $\{c_k\}$ is the pseudo-random code sequence and the chip duration is assumed to be the same as the pulse duration i.e. $T_c = T_p$.

B. Channel models

We consider two different wideband channel models - the first is the conventional channel model based on an L-tap delay line with a multipath component at each delay and the second is that adopted by the IEEE 802.15.3a task group based on the Saleh-Valenzuela model.

1) Conventional tapped delay-line model: In a time-invariant multipath channel, the received signal is given by

$$s_{rec}(t) = s(t) * h(t) + n(t) \quad (4)$$

where $h(t)$ is the impulse response of the channel and $n(t)$ is a zero mean additive white Gaussian noise process with a power spectral density of N_0. The wideband UWB channel can be represented by a tapped delay-line model with the spacing of a minimum multipath resolution t_s, that is determined by the bandwidth of the system. For convenience, we set $t_s = T_p/M$, where T_p is the pulse duration and M is a positive integer.

$$h(t) = \sum_{l=1}^{L}\alpha_l\delta(t-(l-1)t_s) + n(t) \quad (5)$$

where L denotes the number of resolvable paths. In our analysis, we assume an exponentially decaying multipath intensity profile with a decay factor of η; this was assumed as the model for indoor channels in the 2.45 GHz ISM band by the standards group for IEEE 802.11b Wireless LANs. When the total power in all the resolvable paths is normalized to unity, the (average) power in the l-th path is expressed as

$$E[\alpha_l^2] = \frac{1-e^{-\eta}}{1-e^{-\eta L}}e^{-(l-1)\eta} \quad (6)$$

The tap weights are modeled as having independent log-normal distributions, which has been found to be a good fit from some experimental wideband channel measurements [15]. It is important to note that the channel model coefficients are assumed *real* and not complex; while the complex base-band model is a natural fit for narrowband bandpass systems (to capture the phase dependance as a function of frequency), a real model suffices for a wideband but baseband modulation as in UWB [16].

2) IEEE 802.15.3a channel model: Many indoor channels display a certain 'sparseness' when modeled as a delay line with spacing $1/B$, i.e. there does not exist a multipath arrival at each resolved lag component. Rather the paths arrive in clusters implying the possibility of a more efficient representation. The model adopted by the IEEE 802.15.3a for UWB propagation in 3-10 GHz band is a (frequency selective) delay line based on the celebrated Saleh-Valenzuela (S-V) model [16]. This is characterized by two Poisson distributions for the arrival times - one for the delay of the first path of each cluster T_l, that has a mean (cluster) arrival rate of Λ and the second for the paths within each cluster $\tau_{k,l}$ with a mean (path) arrival rate of λ. The distributions of the cluster and path arrival times are thus given by

$$\begin{aligned} p(T_l|T_{l-1}) &= \Lambda\exp\left[-\Lambda(T_l-T_{l-1})\right] \\ p(\tau_{k,l}|\tau_{(k-1),l}) &= \lambda\exp\left[-\lambda(\tau_{k,l}-\tau_{(k-1),l})\right] \end{aligned} \quad (7)$$

Therefore, the multipath channel has the following discrete time impulse response.

$$h(t) = \sum_{l=0}^{L-1}\sum_{k=0}^{K-1}\beta_{k,l}\delta\left(t-T_l-\tau_{k,l}\right) \quad (8)$$

where $\beta_{k,l}$ are the *real* multipath gain coefficients corresponding to a baseband model. The multipath intensity profile is defined by a double exponential decay model

$$E\left[\beta_{k,l}^2\right] = \Omega_0 e^{-T_l/\Gamma}e^{-\tau_{k,l}/\gamma} \quad (9)$$

where Ω_0 is the mean power of the first path of the first cluster and Γ and γ are the cluster and path decay factors respectively. The amplitudes are assumed to be independent log-normal distributions.

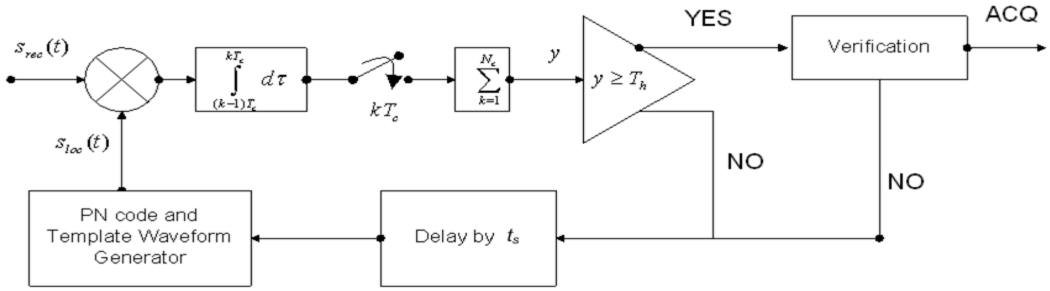

Fig. 1. Structure of an acquisition receiver employing serial search

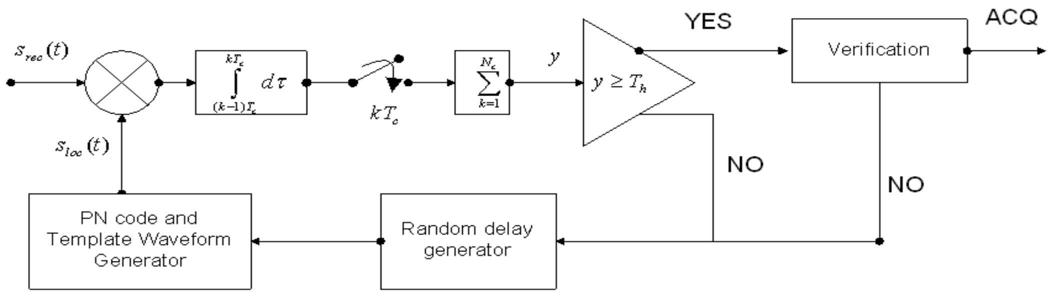

Fig. 2. Structure of an acquisition receiver employing random search

III. Receiver Architecture

A. Serial Search Acquisition

The conventional method used to synchronize the received signal with the receiver's local code is the serial search scheme using the sliding correlator [17] shown in Fig 1. The phase of the locally generated code is progressively shifted in sequence in steps of a unit search interval t_s (set to be equal to the minimum multipath resolution) and a decision variable formed by correlating the local code with the received code over the correlator dwell time. Since we only consider short codes in this work, the correlator dwell time is assumed to be one full period of the PN code, i.e. $\tau_D = N_c T_c$. The decision variable is then compared with a decision threshold T_h. If the decision variable exceeds the threshold, the corresponding cell is declared to be an in-phase cell (H_1 cell) and the search is terminated. Otherwise, the cell is declared to be an out-of-phase cell (H_0 cell) and the next cell is tested. The entire process is repeated until the codes are aligned (to within a step size ambiguity). The total number of cells in the uncertainty region is thus $q = N_c T_c / t_s = N_c M$. In the event of a false alarm, it is assumed that the search resumes after a penalty time of J correlator dwell times, which is the time taken to confirm the false alarm.

B. Random Search Acquisition

The random search acquisition receiver is very similar to the serial search receiver except that the local code is not shifted serially. Instead, the correlator step size at any time is chosen randomly as shown in Fig 2. The random delay generator changes the phase of the PN code randomly between 1 and $(q-1)$ step sizes. The receiver continues to run with random jumps at each step until acquisition is achieved, which is defined as the state when the receiver locks on to any one of the H_1 cells to within a step size ambiguity.

IV. Performance Analysis

We next derive expressions for mean acquisition times (MAT) for the serial and random searches that are verified with simulations. The MAT expressions derived in IV-A.1 and IV-A.2 are new to the best of our knowledge.

A. Performance in conventional multipath model

Owing to the presence of L multipath components, the uncertainty region in multipath contains L H_1 cells and the remaining $(q-L)$ cells are H_0 cells. For an H_0 cell, the output y of the correlator is a zero-mean Gaussian random variable with a variance of $N_c N_0$. In the H_1 cells, the timing error between the local and the received codes is within half a step-size duration. Also, each H_1 cell in the multipath case is associated with its own probability of detection P_{D_l}, determined by the corresponding path gain α_l. Under H_1 hypothesis for the l^{th} cell, the decision variable y is now a Gaussian random variable with a variance of $N_c N_0$, while its mean is equal to $N_c \alpha_l \sqrt{E_c} R_p(\xi)$, where $R_p(\tau)$ is the normalized pulse auto-correlation function in (2) and ξ is the timing error in a H_1 cell. We introduce a normalized threshold Υ_{th} related to T_h via $T_h = \Upsilon_{th} N_c \sqrt{E_c}$. Therefore, for a given fading amplitude and a timing error, the probability of detecting the l^{th} H_1 cell is

$$\begin{aligned} P_{D_l}(\Upsilon_{th}|\xi, \alpha_l) &= Pr\left(|y| > T_h | H_1\right) \\ &= Q\left(\sqrt{\frac{N_c E_c}{N_0}}\left(\Upsilon_{th} - \alpha_l R_p(\xi)\right)\right) \\ &\quad + Q\left(\sqrt{\frac{N_c E_c}{N_0}}\left(\Upsilon_{th} + \alpha_l R_p(\xi)\right)\right) \end{aligned} \tag{10}$$

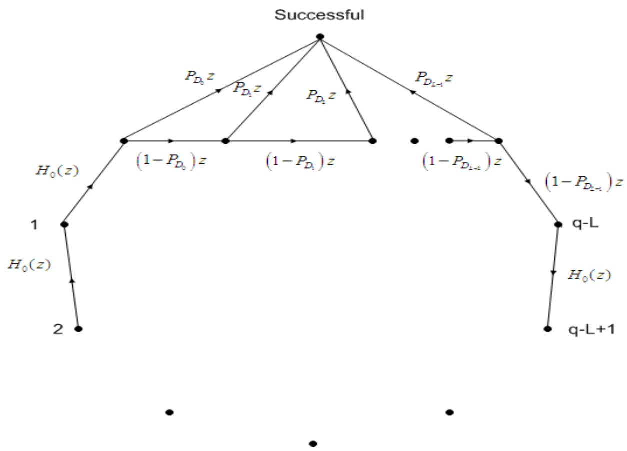

Fig. 3. Circular state diagram for the serial search acquisition system in multipath

It is further assumed that the PN code has perfect auto-correlation properties. Therefore, the mean of y in a H_0 cell is zero. The probability of false alarm is then given by

$$P_{FA}(\Upsilon_{th}) = Pr\left(|y| > T_h | H_0\right) = 2Q\left(\sqrt{\frac{N_c E_c}{N_0}}\Upsilon_{th}\right) \qquad (11)$$

1) Serial Search: The traditional analyses of the serial search scheme performed in [11] and [12] make the assumption that the number of H_1 cells (L) is negligible compared to the total number of cells (q) in the search space; this is clearly invalid for the acquisition of UWB signals. In the following, we analyze the serial search scheme without the assumption. In order to do this, we consider the transfer function starting from a H_0 cell to the ACQ state as distinct from that starting from a H_1 cell to the ACQ state . The relevant state diagram for acquisition in multipath is shown in Fig 3.

(i) Given that the search starts in a H_0 cell that is i cells to the left of the first H_1 cell, the transfer function to reach the ACQ state is given by

$$H_i(z)_{(H_0)} = \frac{H_0^i(z) H_D(z)}{1 - H_M(z) H_0^{(q-L)}(z)} \qquad (12)$$

where $H_0(z)$ is the transfer function for exiting a H_0 cell, $H_D(z)$ is the transfer function denoting absorption into the ACQ state starting from the first H_1 cell before encountering a H_0 cell and $H_M(z)$ is the transfer function denoting a total miss in any round.

$$\begin{aligned} H_0(z) &= P_{FA} z^{J+1} + (1 - P_{FA}) z \\ H_D(z) &= \textstyle\sum_{j=1}^{L} P_{D_j} z \prod_{k=1}^{j-1} (1 - P_{D_k}) z \\ H_M(z) &= \textstyle\prod_{j=1}^{L} \left(1 - P_{D_j}\right) z \end{aligned}$$

(ii) Given that the initial cell is the i^{th} H_1 cell, the transfer function to reach the ACQ state is given by

$$H_i(z)_{(H_1)} = H_{D_r}(z) + H_{M_r}(z) H_{q-L}(z)_{(H_0)} \qquad (13)$$

where $H_{D_r}(z)$ is the transfer function denoting absorption into the ACQ state starting from the i^{th} H_1 cell before encountering a H_0 cell and $H_{M_r}(z)$ is the transfer function of missing the H_1 cells numbered i through L.

$$\begin{aligned} H_{D_r}(z) &= \textstyle\sum_{j=i}^{L} P_{D_j} z \prod_{k=i}^{j-1} (1 - P_{D_k}) z \\ H_{M_r}(z) &= \textstyle\prod_{j=i}^{L} \left(1 - P_{D_j}\right) z \end{aligned}$$

Since each cell has a uniform probability of $1/q$ of being the starting cell, the overall transfer function of the serial search is given by

$$H(z) = \frac{1}{q}\left[\sum_{i=1}^{q-L} H_i(z)_{(H_0)} + \sum_{i=1}^{L} H_i(z)_{(H_1)}\right] \qquad (14)$$

The mean acquisition time can then be obtained by

$$\overline{T}_{acq} = \left.\frac{dH(z)}{dz}\right|_{z=1} \times \tau_D \qquad (15)$$

$\overline{T}_{acq}$ is given by (16) at the bottom of this page, where

$$\begin{aligned} T_D &= \textstyle\sum_{j=1}^{L} j P_{D_j} \prod_{k=1}^{j-1} (1 - P_{D_k}) \\ P_M &= \textstyle\prod_{k=1}^{j-1} (1 - P_{D_k}) \end{aligned} \qquad (17)$$

At high signal-to-noise ratios when $P_{FA} \to 0$ and $P_{D_i} \to 1$, $\forall i$, the process takes one integration time to reach the ACQ state if the search falls in any of the H_1 cells and $(i+1)$ integration times if it falls in a H_0 cell i cells to the left of the first H_1 cell. Therefore, $\overline{T}_{acq}$ reduces to

$$\begin{aligned} \overline{T}_{acq}(sat) &= \frac{1}{q}\left[L + \sum_{i=1}^{q-L}(i+1)\right] \times \tau_D \\ &= \frac{2(L-1) + (q-L+1)(q-L+2)}{2q}\tau_D \end{aligned} \qquad (18)$$

$$\begin{aligned} \overline{T}_{acq} &= \frac{q-L}{q}\left(\frac{2T_D + (q + qP_M - L + 1 - P_M)(1 + JP_f) + LP_M(1 - JP_f)}{2(1 - P_M)}\right)\tau_D \\ &+ \frac{1}{q}\left(\sum_{i=1}^{L}\sum_{j=i}^{L}(j - i + 1) P_{D_j} \prod_{k=i}^{j-1}(1 - P_{D_k})\right)\tau_D \\ &+ \frac{1}{q}\left(\sum_{i=1}^{L}\left(\frac{T_D + (q-L)(1 + P_f J) + LP_M}{(1 - P_M)} + (L - i + 1)\right)\left(\prod_{k=i}^{L}(1 - P_{D_j})\right)\right)\tau_D \end{aligned} \qquad (16)$$

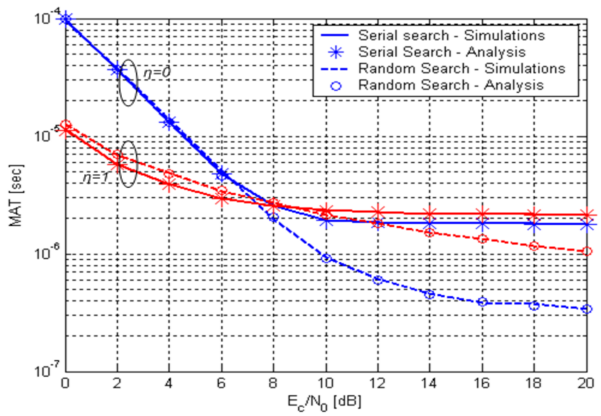

Fig. 4. Mean acquisition time in conventional multipath channel: L=16

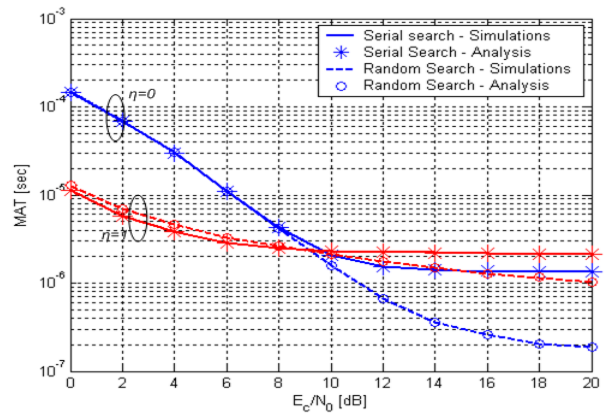

Fig. 5. Mean acquisition time in conventional multipath channel: L=32

2) Random Search: The state diagram of random search would have the H_1 cells dispersed randomly among the H_0 cells. The overall transfer function can still be derived by noting that when the process is in a H_0 cell, it has a $1 - L/q$ probability of transitioning to a H_0 cell in the next step and a $1/q$ probability of transitioning to each of the H_1 cells. Therefore, the transfer function for exiting an H_0 cell is given by

$$H_0(z) = \left[P_{FA}z^{J+1} + (1 - P_{FA})z\right] \times \left[\left(\frac{q-L}{q}\right) H_0(z) + \left(\frac{1}{q}\right) \sum_{i=1}^{L} H_i(z)\right] \quad (19)$$

where $H_i(z)$ is the transfer function for exiting the i^{th} H_1 cell. On the other hand, when the search is in the i^{th} H_1 cell, it could move to the ACQ state with a probability of P_{D_i}, to a H_0 cell with a probability of $(1-P_{D_i})(q-L)/q$ and to each of the remaining H_1 cells with a probability of $(1-P_{D_i})1/q$. Therefore the transfer function from the i^{th} H_1 cell is given by

$$H_i(z) = P_{D_i}z + (1 - P_{D_i})z \times \left[\left(\frac{q-L}{q}\right) H_0(z) + \left(\frac{1}{q}\right) \sum_{j=1}^{L} H_j(z)\right] \quad (20)$$

The $H_i(z)$'s and $H_0(z)$ can be obtained by simultaneously solving the $L+1$ equations obtained from (19) and (20). Since the search has a $(q-L)/q$ probability of starting in a H_0 cell and a $1/q$ probability of starting in each of the H_1 cells, the effective transfer function to reach the ACQ state is given by

$$H(z) = \left(\frac{q-L}{q}\right) H_0(z) + \left(\frac{1}{q}\right) \sum_{i=1}^{L} H_i(z) \quad (21)$$

The mean acquisition time is again calculated using (15). For random search, the formula for the mean acquisition can be shown to be given by the closed form

$$\boxed{\overline{T}_{acq} = \frac{P_{FA}J(q-L) + q}{\sum_{l=1}^{L} P_{D_l}} \times \tau_D} \quad (22)$$

In random search at high signal-to-noise ratio values, the probability that the search lands in a H_1 cell is L/q and the number of jumps to get to a H_1 cell follows a geometric distribution with a mean of q/L. Therefore the mean acquisition time at high signal-to-noise ratios is

$$\overline{T}_{acq}(sat) = \left(\frac{q}{L}\right) \tau_D \quad (23)$$

which is the same as predicted by the above formula.

3) Simulations: We verified the above observations by means of simulations using a UWB pulse of width 1 ns and a PN code of length 32. The multipath channel having an exponential power delay profile was simulated with different delay spreads and decay factors. The threshold setting was based on constant false alarm rate (CFAR) with $P_{FA} = 10^{-4}$ and the step size for the correlator was fixed to be a fourth of the pulse duration, i.e., $M = 4$. Fig 4 shows the results of the simulations for a delay spread of 4 ns and Fig 5 for a delay spread of 8 ns. Both the figures show results for two decay factors, $\eta = 0$ (uniform MIP) and $\eta = 1$.

The first observation is that the simulation results for the serial and random searches match exactly those predicted by analysis. Also it is clear that it becomes increasingly advantageous to adopt the random search over serial search as the multipath profile becomes more uniform. The advantage of random search is that it requires fewer steps on the average to reach a H_1 cell than serial search when the number of paths is large. On the other hand, the serial search has the advantage that it encounters cells with higher probability of detection earlier than those with lower probability of detection when the multipath intensity profile is exponential (not so when the profile is more uniform). It thus takes a larger SNR for the natural advantage of random search to outweigh that of serial search for an exponential multipath profile as the decay factor is increased.

The performance advantage of random search over serial search as a function of the number of multipath components is examined by comparing Figs 4 and 5. It is evident that the advantage increases as the number of multipaths increases. This is due to the fact that as the number of paths increases, the mean number of steps required to reach a H_1 cell decreases faster for random search than for serial search. In summary,

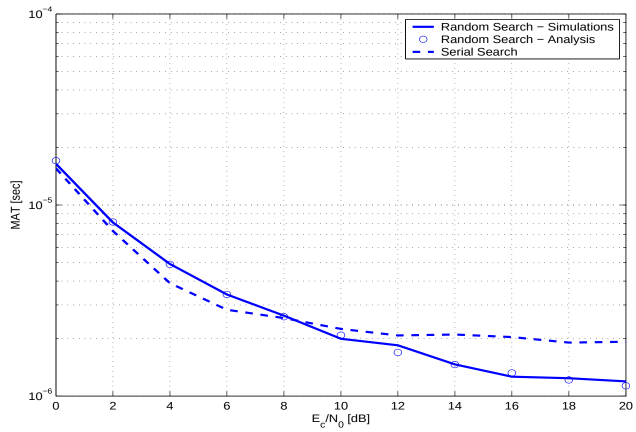

Fig. 6. Mean acquisition time in the IEEE 802.15.3a channel model

random search gives the most benefit when the multipath profile is uniform and the number of multipath components is large.

B. Performance in IEEE 802.15.3a channel model

The analysis of the random search scheme performed in Section IV-A.2 and the expression for mean acquisition time derived therein do not make any assumption about the channel model. Since the channel model only affects the probabilities of detection and false alarm, the MAT formula in (22) can be used for the IEEE802.15.3a channel model as well. The serial search analysis in Section IV-A.1 however is based on the assumption that multipath components are present on contiguous tap positions and therefore would not apply for the IEEE 802.15.3a model. The fact that there is a finite probability that there could be H_0 cells interspersed among the H_1 cells complicates the analysis. We therefore resorted to simulations to evaluate the performance of the serial search scheme.

For our simulations, we still considered a UWB pulse of width 1 ns and a PN sequence of length 32. We simulated a channel based on the IEEE 802.15.3a model with $1/\Lambda = 10$ ns and $1/\lambda = 1$ ns. Threshold setting was based on CFAR with a $P_{FA} = 10^{-4}$. The results of the simulations are plotted in Fig 6, which shows the acquisition times of the conventional serial search and random search schemes. For random search, the MAT values obtained from the formula match those obtained from simulations pretty well. Also noticeable is the fact that the performance of serial search is not significantly different from random search. The inherent randomness of the multipath arrivals in the 802.15.3a channel model renders serial search performance to be very similar to random search. As the multipath arrivals become more random, i.e., the H_1 cells become more uniformly dispersed among H_0 cells, the performance of serial search scheme would become indistinguishable from that of random search. This underscores the broad utility of the random search analysis developed - it can be used as a good model for *any* deterministic search scheme where the multipath profile is ‘randomized’.

V. Conclusions

We provide a new analysis of serial search by removing assumptions invoked for conventional wideband systems that are not valid for UWB. We have also derived an expression for the mean acquisition time for random search for any general multipath channel model. It has been shown that the random search provides significant improvement in performances over serial search when the number of multipath components is large and especially when the multipath profile is more uniform. Typical UWB channel models tend to have random multipath arrivals, and any deterministic search scheme would behave much like random search. Thus the analysis provided in this paper should prove to be very useful in estimating the acquisition times in typical UWB channels.

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