Rapid Acquisition of Ultra-Wideband Signals in the Dense Multipath Channel

Eric A. Homier

Communications Sciences Institute
Dept. of Electrical Engineering - Systems
University of Southern California

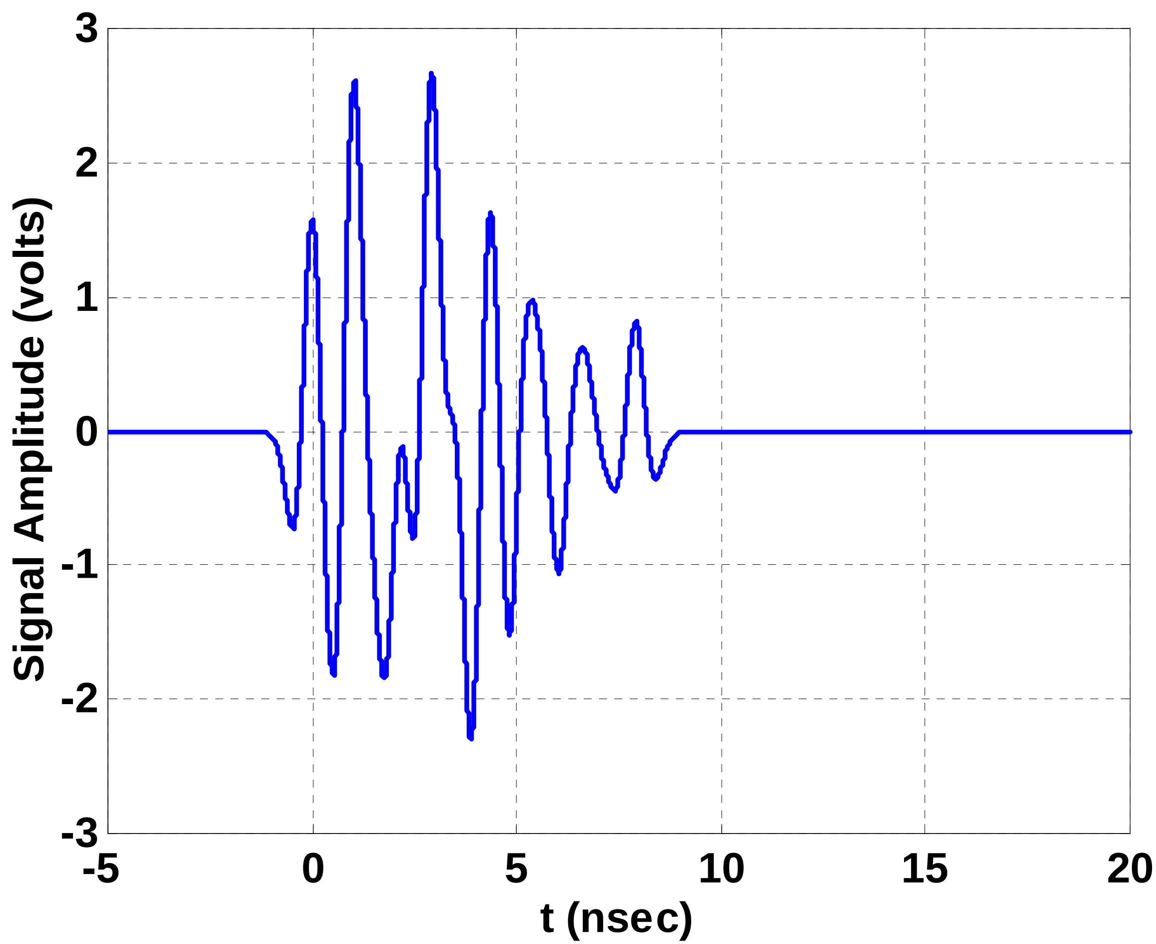
May 21, 2002

Overview of the Talk

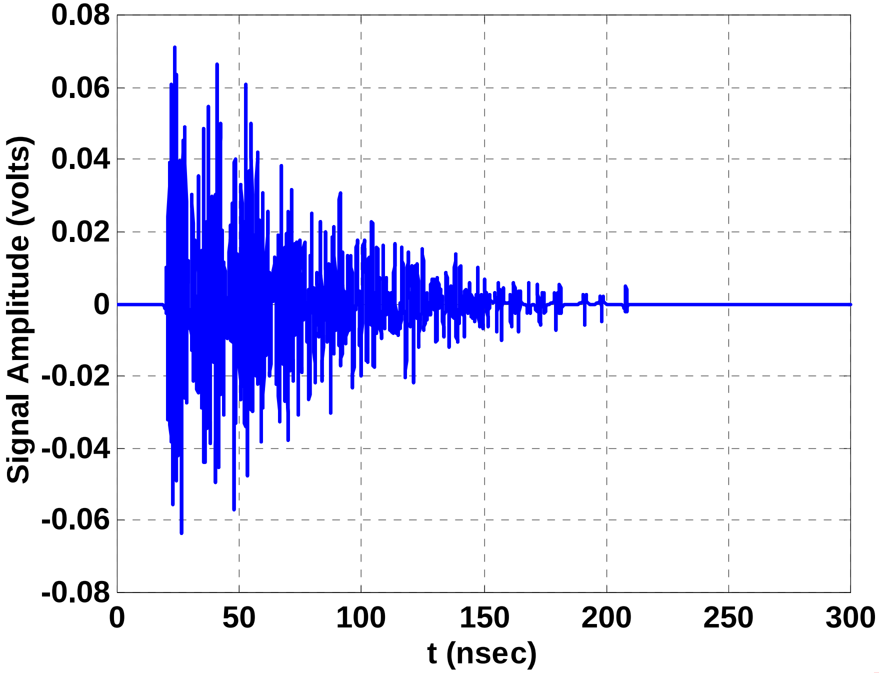
- Background Material
  - UWB Signal and Multipath Channel
  - Two examples of multipath channels:
    - Indoor office environment
    - Hold of Navy Cargo Ship
- Synchronization Background
  - Classic Serial Searches
  - Hybrid Serial/Parallel Search
- Acquisition of UWB Systems
  - Single-User Frame Acquisition

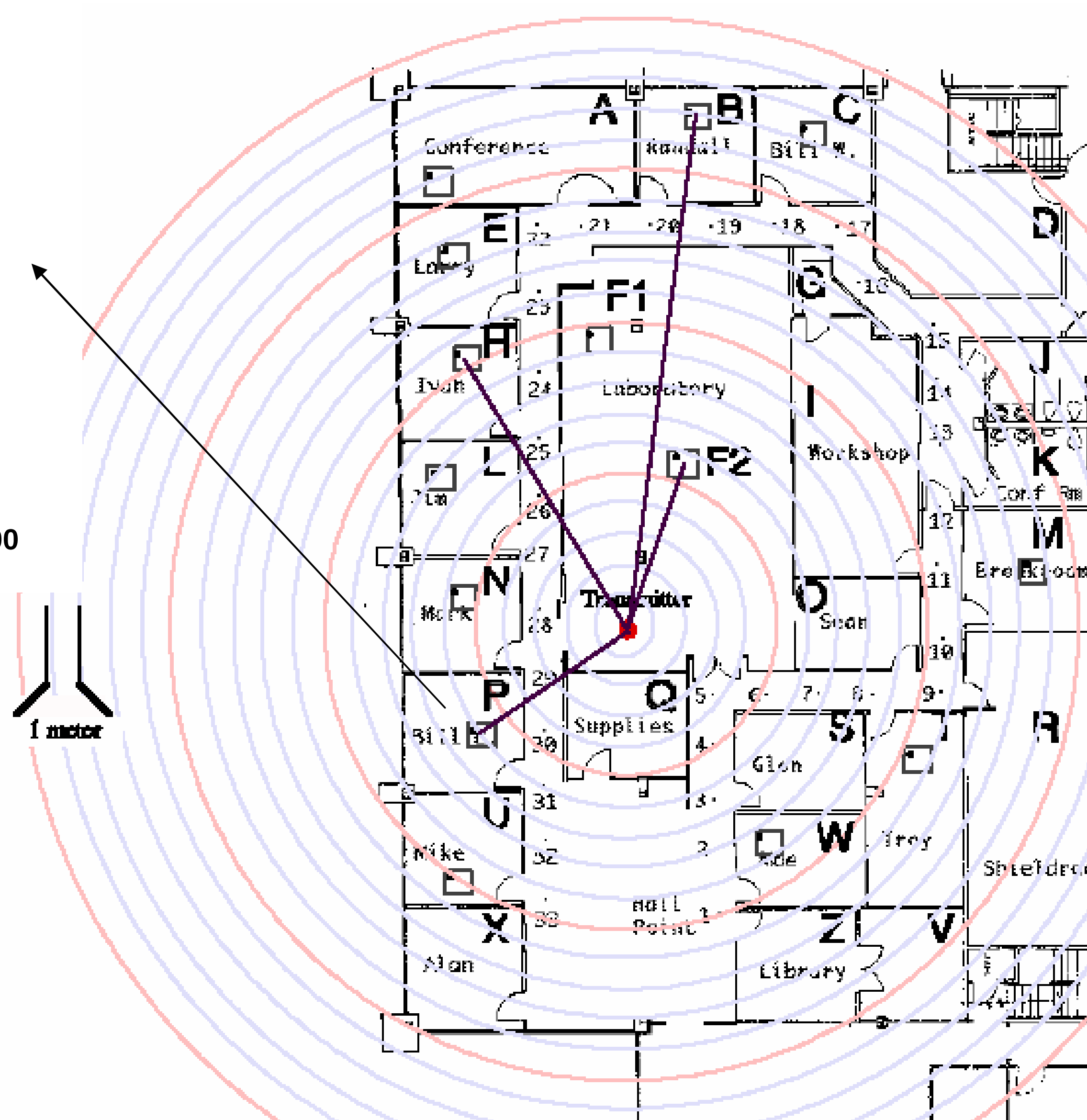
Ultra-Wideband Signal Shape

- Free space UWB received signal is 2nd derivative Gaussian pulse
- Multipath channel is determined by specular model: $h(t)=\sum_{m=0}^{M_p-1} a_m \delta(t-\tau_m)$



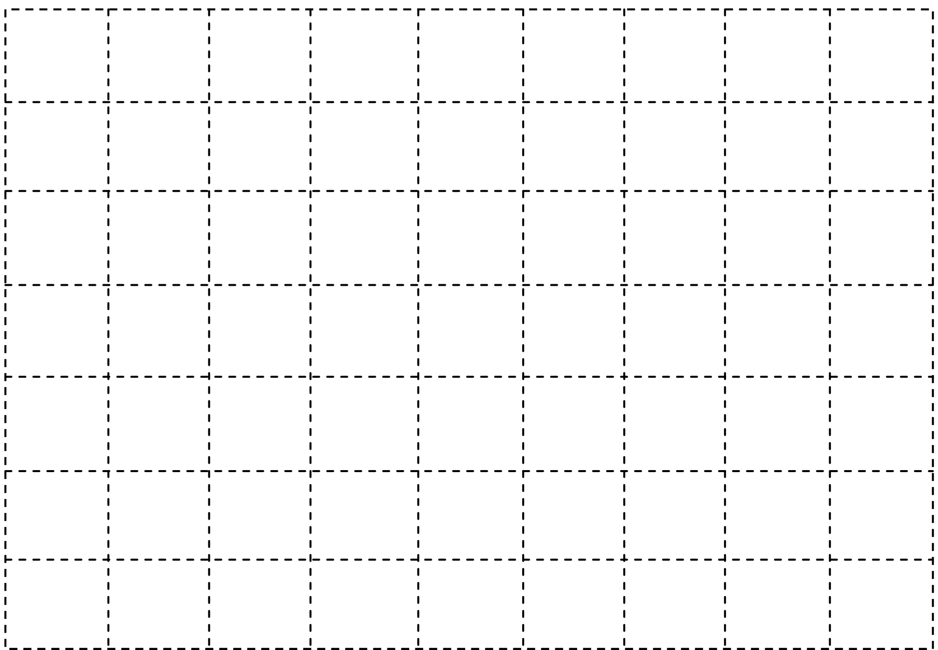
Multipath channel output for indoor office environment:





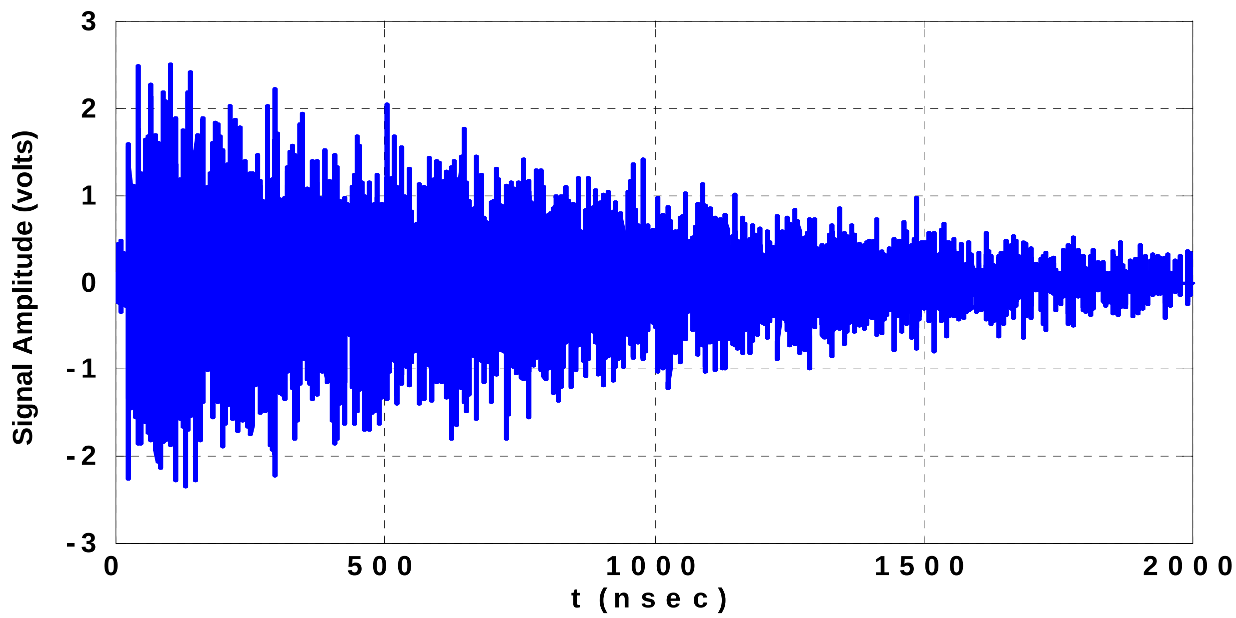
- Delay spread of this environment is around 200 nsec

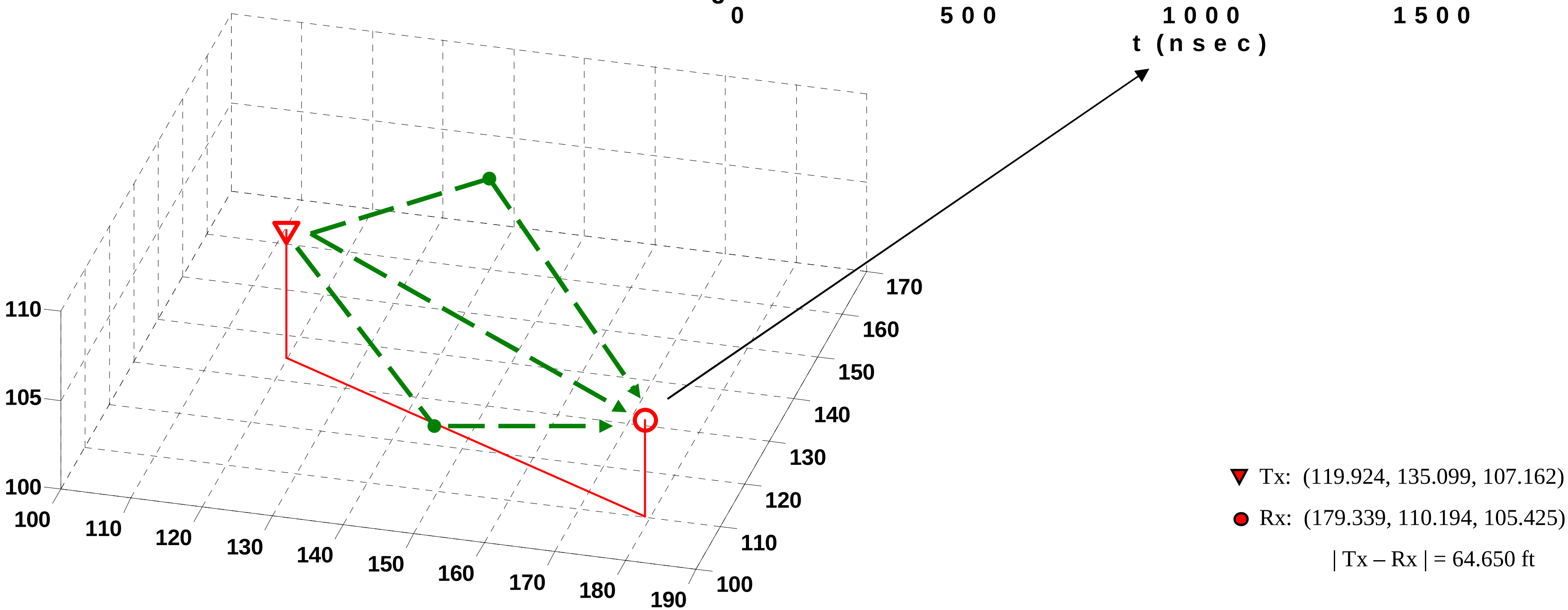
SS Curtiss 2nd Deck - Top View



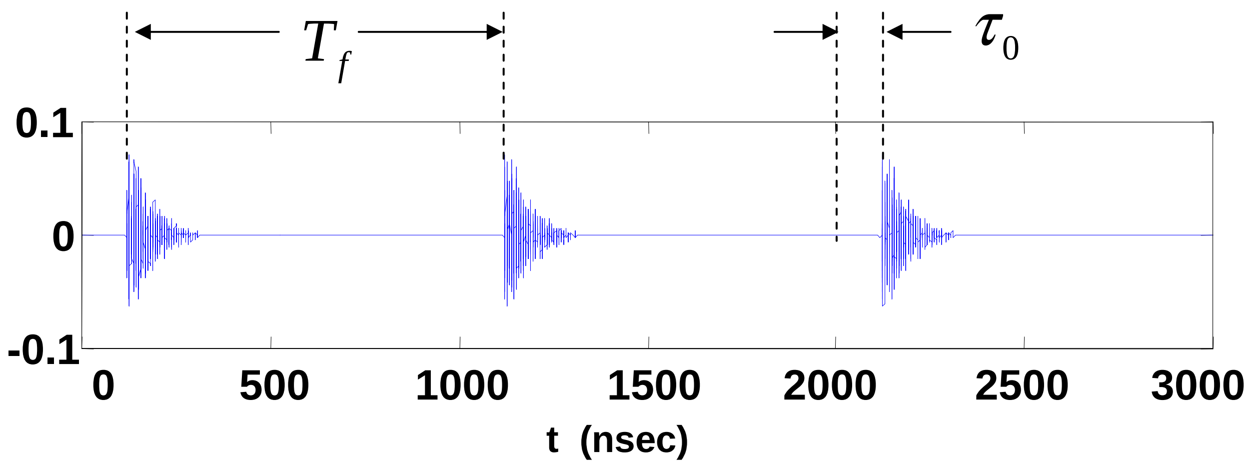
Multipath channel output in cargo hold:

- Delay spread of this environment is around 2000 nsec (10x the office environment!)



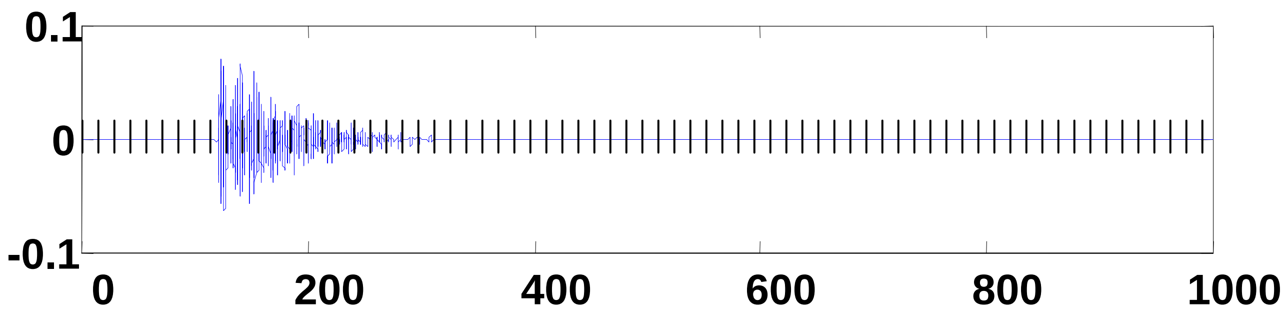


Frame Structure



- First arrival time, τ_0, is uniform over $[0, T_f)$
- Remaining arrival times, τ_m, and all the amplitude coefficients, a_m, are *unknown* to the receiver
- Path arrivals within a ‘cluster’ are highly correlated spatially (and temporally)
- How does a RAKE receiver *quickly* select it’s tap delays and amplitude coefficients?

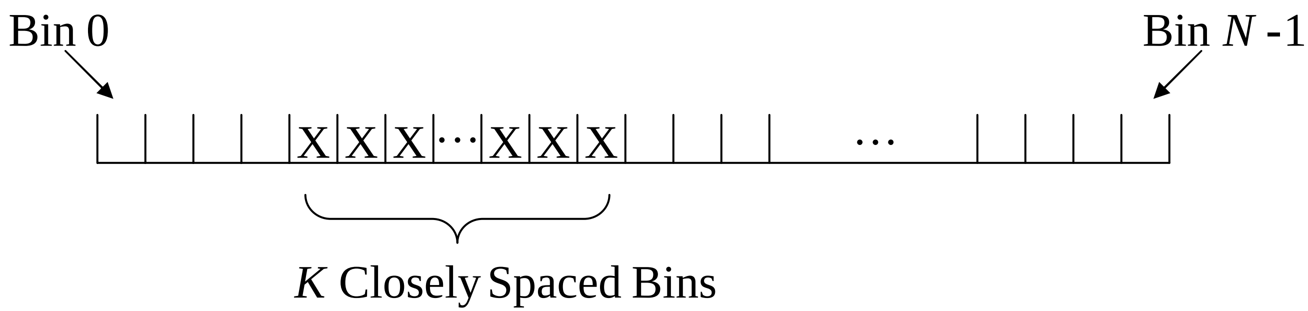
Hybrid Serial/Parallel Search



- Frame is divided into N equally spaced bins
- *Coarse* search is first performed to locate the ‘cluster’
- *Fine* search follows and selects the strongest paths
- Correlators of RAKE yield multiple observations serially – ‘hybrid’ search
- Given this approach, how does the RAKE quickly locate the ‘cluster’?
- A simple approach is to use a single search pattern divided amongst the RAKE correlators

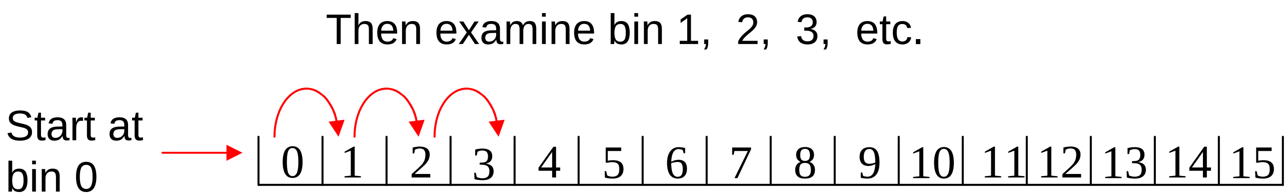
Serial Search

- Simplest search is ‘linear’ – as in classical CDMA code sync
- Linear search assumes only a single bin (or small group of bins) will result in proper termination
- This single bin assumption is invalid for the types of UWB systems at hand

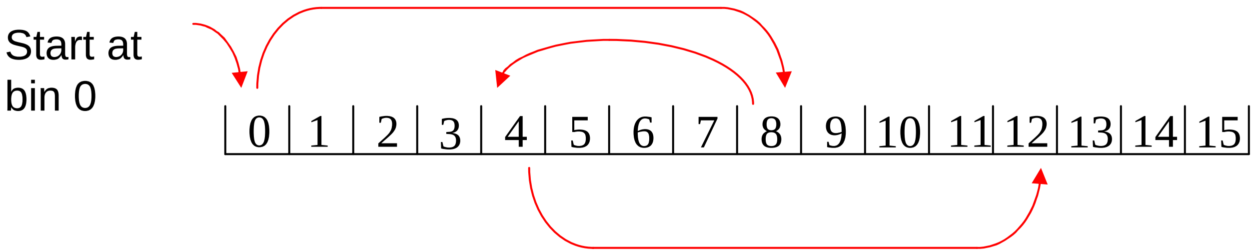


Different Types of Serial Searches

- Linear Search

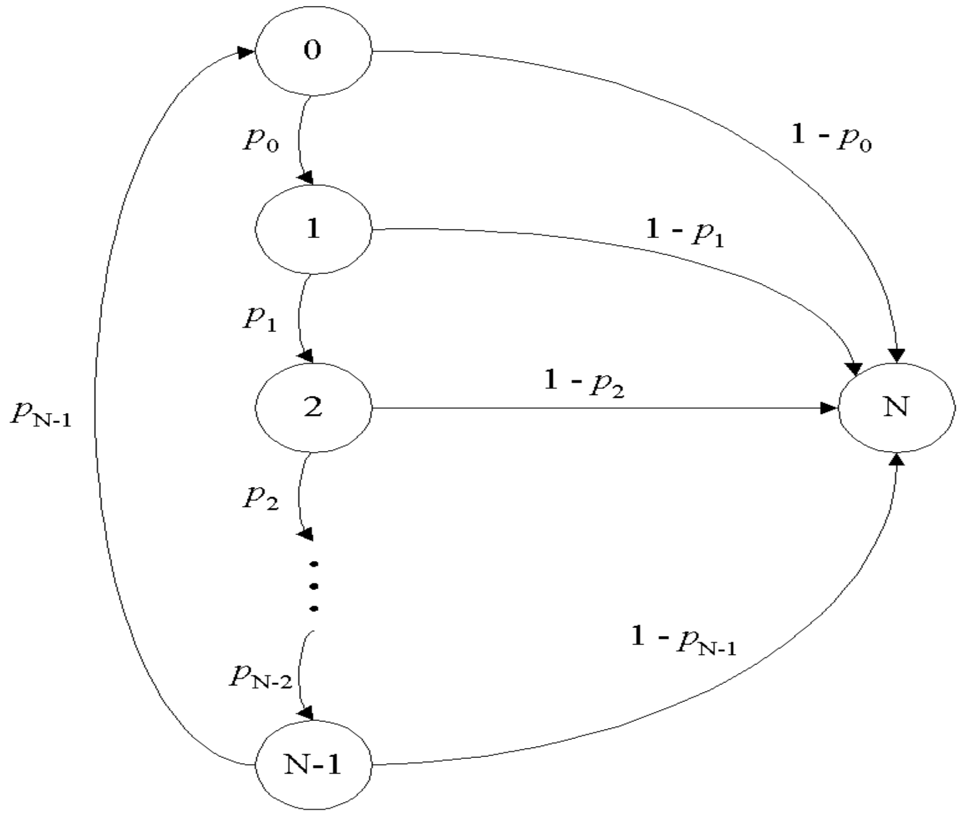


- Truly Random Search: Bins selected at random from $0, 1, \ldots, N-1$.
- Random Permutation Search: Random permutation of the integers and the mean stopping time is averaged over all such permutations
- 'Look and Jump by K Bins' Search: The search order is bin 0, bin K, bin $2K$, etc.
- Bit Reversal Search: The linear search indices are 'bit reversed'. For $N = 2^4$ the indices 0000, 0001, 0010, …, 1110, 1111 are bit reversed to yield the search order: 0000, 1000, 0100, …., 0111, 1111



Markov Model for Search

- Simplest type of search 'verification' is single dwell which is assumed here.
- Each of the N bins is assigned as a state in a Markov chain, where the $(N+1)^{st}$ state is an absorbing state representing that the search has terminated.



Search Performance

- Mean time to absorption into state N is:

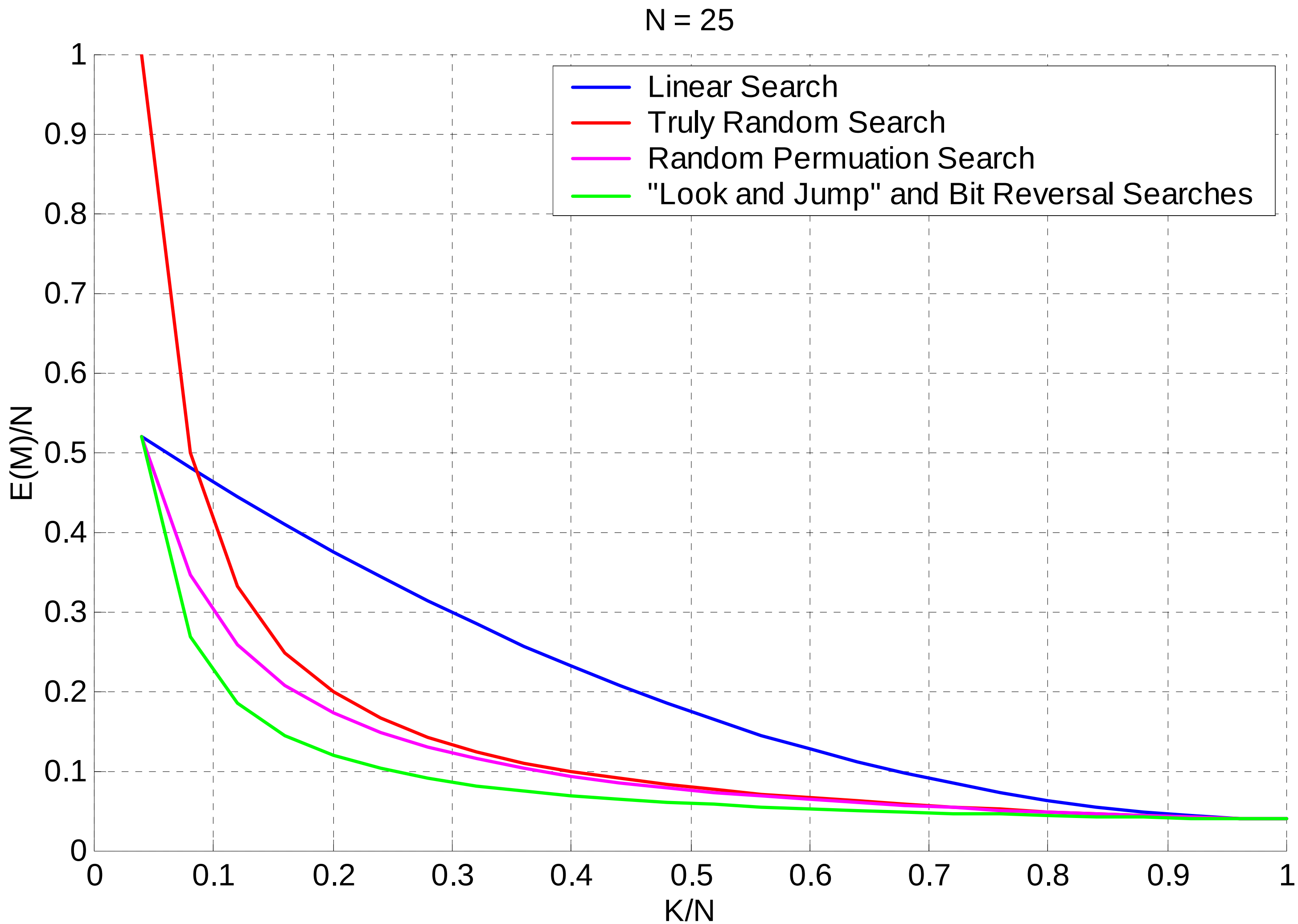
$$E(M)=\frac{1+\sum_{m=0}^{N-2}\prod_{n=0}^{m}p_n}{1-\prod_{n=0}^{N-1}p_n}$$

- Transition probabilities, p_n, are functions of the *proper terminating states* and for UWB this set of states is determined by the multipath channel:

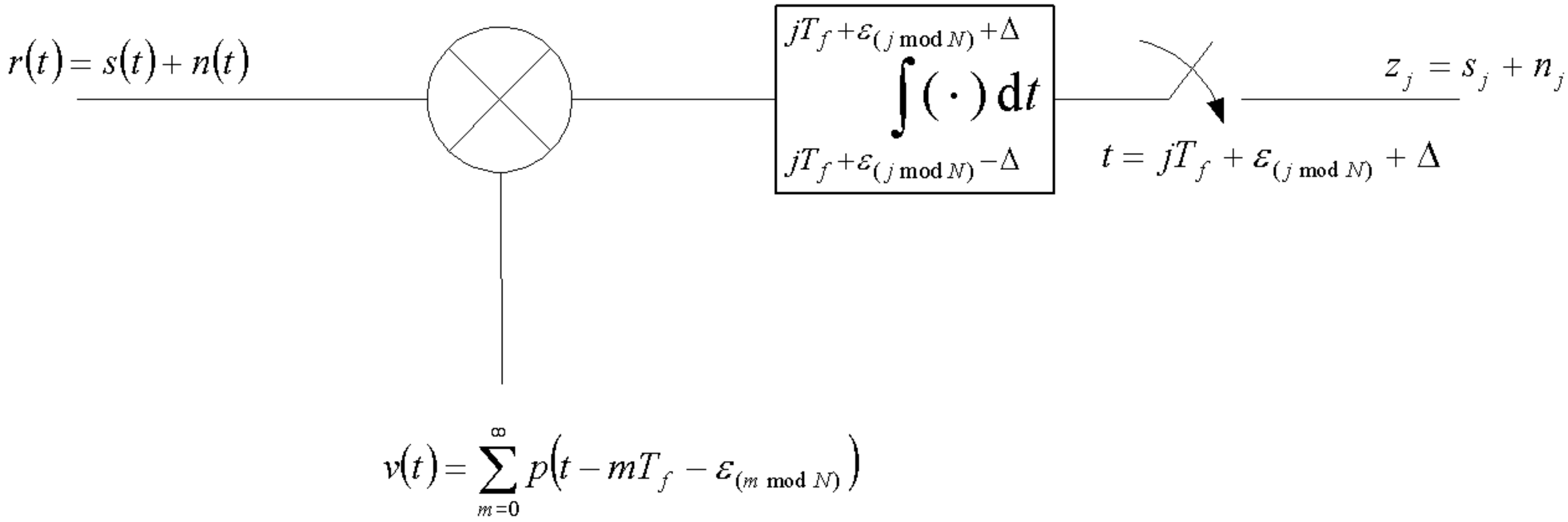
$$E(M)=\int_{\underline{\tau}}\int_{\underline{a}}E\left(M\,|\,\underline{a},\underline{\tau}\right)f\left(\underline{a},\underline{\tau}\right)\mathrm{d}\underline{a}\,\mathrm{d}\underline{\tau}$$

Mean Search Time Example

- The set of terminating states is K consecutive states out of N
- The transition probabilities are limited to one or zero ($P_D = 1$ and $P_{FA} = 0$)



Single Correlator Frame Acquisition



- The search variable ε_n is varied as per linear search, bit reversal search, etc.
- The signal portion of the correlator input is (no time hopping or data modulation):

$$s(t) = \sqrt{E_p} \sum_{n=0}^{\infty} \sum_{k=0}^{M_p - 1} a_k\, p\left(t - nT_f - \tau_k\right)$$

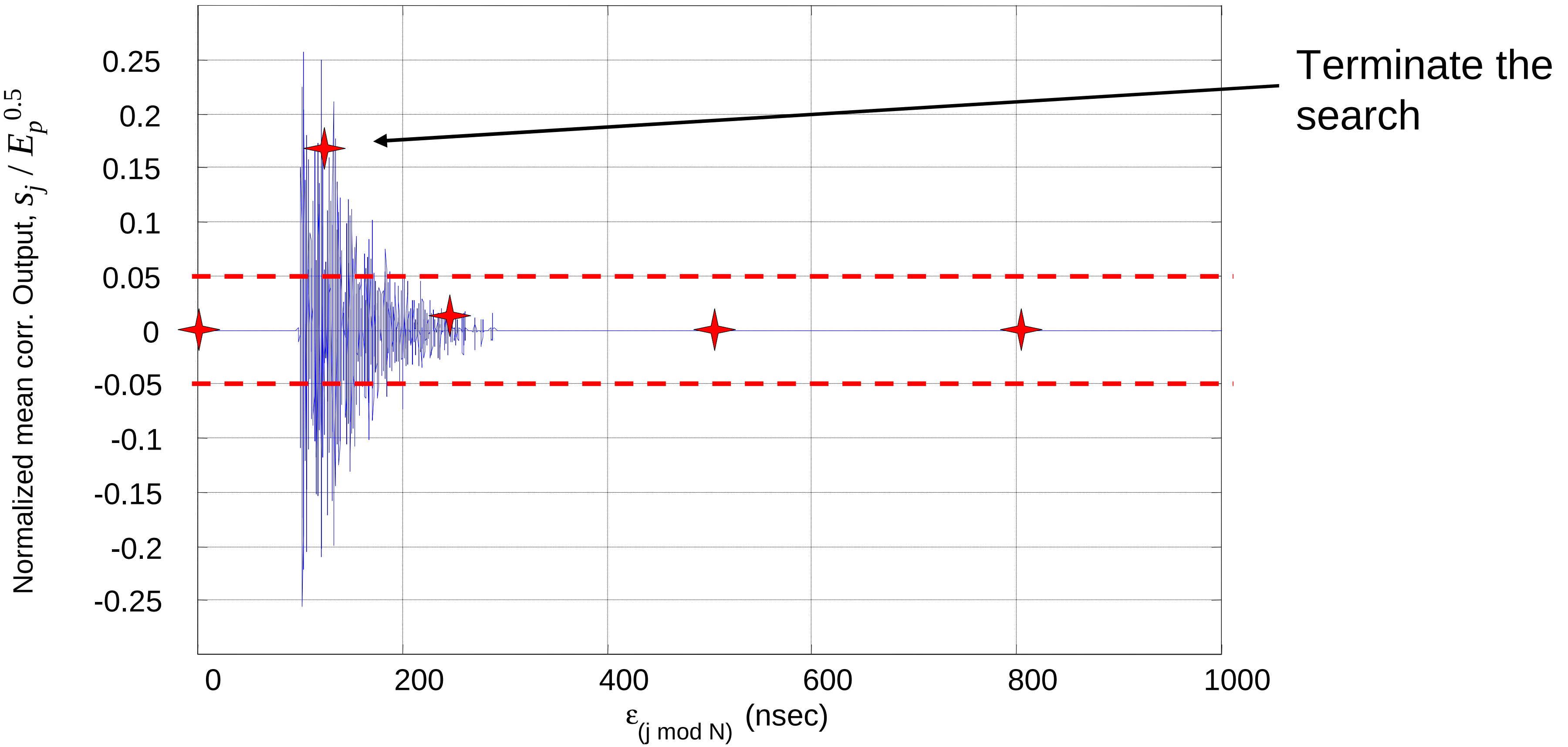
- $n(t)$ is mean zero AWGN with autocorrelation $N_0 \delta(\tau)$ so that noise portion of the correlator output, n_j, is an i.i.d. Gaussian sequence with mean zero and variance N_0.

Single User Frame Acquisition

- The signal potion of the correlator output is:

$$s_j = \sqrt{E_p}\sum_k a_k \cdot \left[\gamma\left(\tau_k - \varepsilon_{(j \bmod N)}\right) + \gamma\left(\tau_k - \varepsilon_{(j \bmod N)} - T_f\right)\right]$$

- For the indoor office channel shown earlier with $\tau_0 = 100$ nsec, $T_f = 1000$ nsec, $\varepsilon_n = (n/N)\,T_f$ with $n = 0,1,\ldots N\text{-}1$ and $N = 8192$ bins



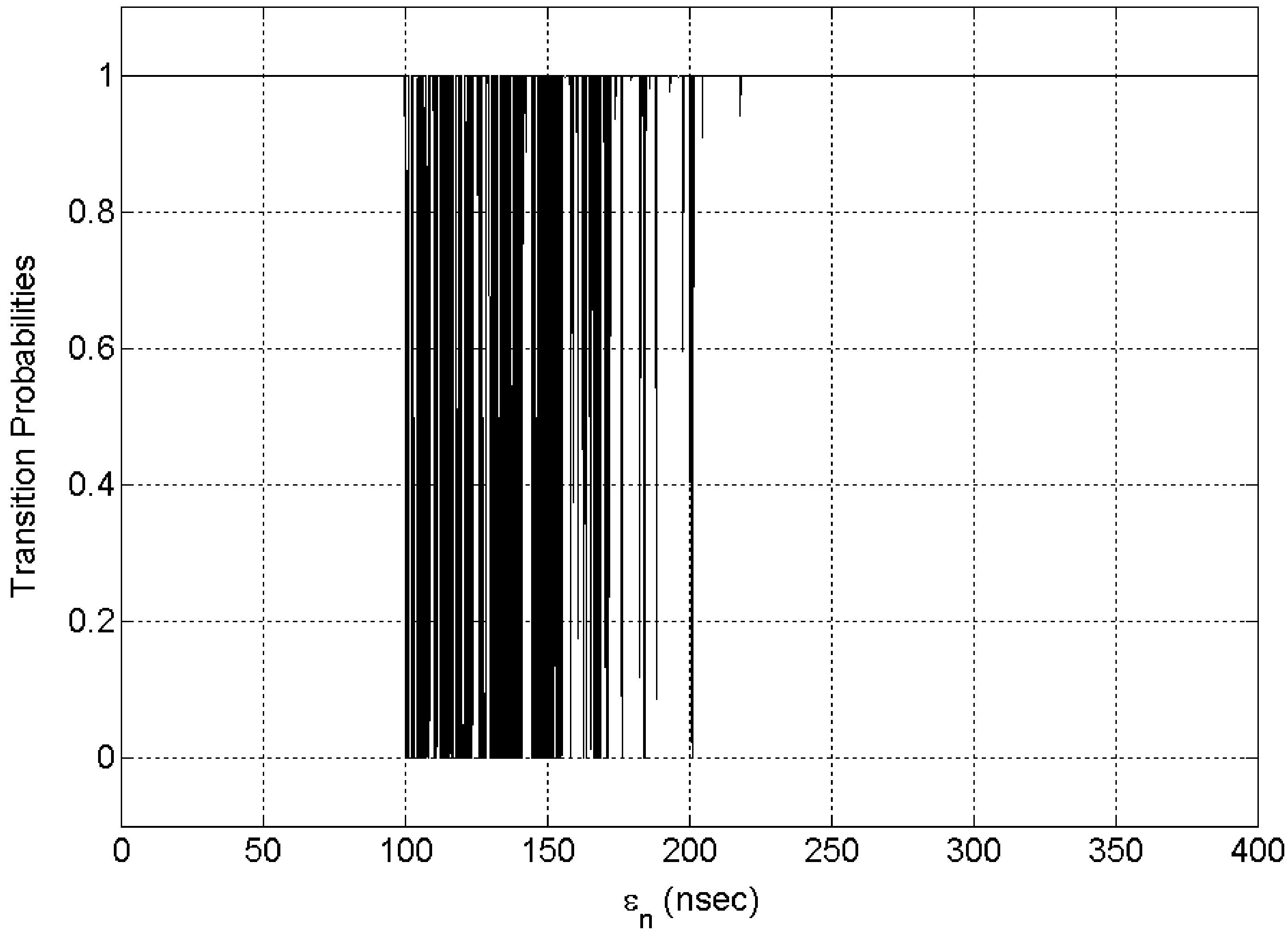
Single User Frame Acquisition

- Single-dwell acquisition: The search terminates the first time the threshold, $\sqrt{E_p}\zeta$, is exceeded.
- The transition probabilities are as follows where $n = j \bmod N$ and $\Delta\tau_k = \tau_k - \tau_0$:

$$
\begin{aligned}
p_n(\tau_0) &= \Pr\left(|z_j| \le \sqrt{E_p}\zeta\right) \\
&= 1 - Q\left(\sqrt{\frac{E_p}{N_0}}\left(\zeta + \sum_k a_k \cdot \left[\gamma(\tau_0 + \Delta\tau_k - \varepsilon_n) + \gamma\left(\tau_0 + \Delta\tau_k - \varepsilon_n - T_f\right)\right]\right)\right) \\
&\quad - Q\left(\sqrt{\frac{E_p}{N_0}}\left(\zeta - \sum_k a_k \cdot \left[\gamma(\tau_0 + \Delta\tau_k - \varepsilon_n) + \gamma\left(\tau_0 + \Delta\tau_k - \varepsilon_n - T_f\right)\right]\right)\right)
\end{aligned}
$$

Single User Frame Acquisition

- The transition probabilities for the indoor environment are shown below for τ_0 = 100 nsec, T_f = 1000 nsec, $\varepsilon_n = (n/N)\, T_f$ with n = 0,1, … N-1 and N = 8192 bins, ζ = 0.05, and E_p/N_0 = 50 dB:



Single User Frame Acquisition

- Here the first arrival time is the only random quantity:

$$E(M)=\frac{1}{T_f}\int_0^{T_f}\frac{1+\sum_{m=0}^{N-2}\prod_{n=0}^{m}p_n(\tau_0)}{1-\prod_{n=0}^{N-1}p_n(\tau_0)}\mathrm{d}\tau_0$$

- For the office environment the following parameters are used: normalized threshold of $\zeta = 0.05$, SNR of $E_p/N_0 = 50$ dB, a frame time of $T_f = 1000$ nsec, $N = 8192$ bins

$$E(M)=3246.6 \text{ observations} \quad \text{(Linear Search)}$$
$$E(M)=28.7 \text{ observations} \quad \text{(Bit Reversal Search)}$$

- For the cargo ship the following parameters are used: normalized threshold of $\zeta = 0.01$, SNR of $E_p/N_0 = 100$ dB, a frame time of $T_f = 4000$ nsec, $N = 32768$ bins

$$E(M)=4224.8 \text{ observations} \quad \text{(Linear Search)}$$
$$E(M)=3.6 \text{ observations} \quad \text{(Bit Reversal Search)}$$

Single User Frame Acquisition

- The terminating bins for the office environment (cargo ship) are approximately consecutive over 100 nsec (2000 nsec) so that $K/N = 100/1000 = 0.1$ ($2000/4000 = 0.5$)