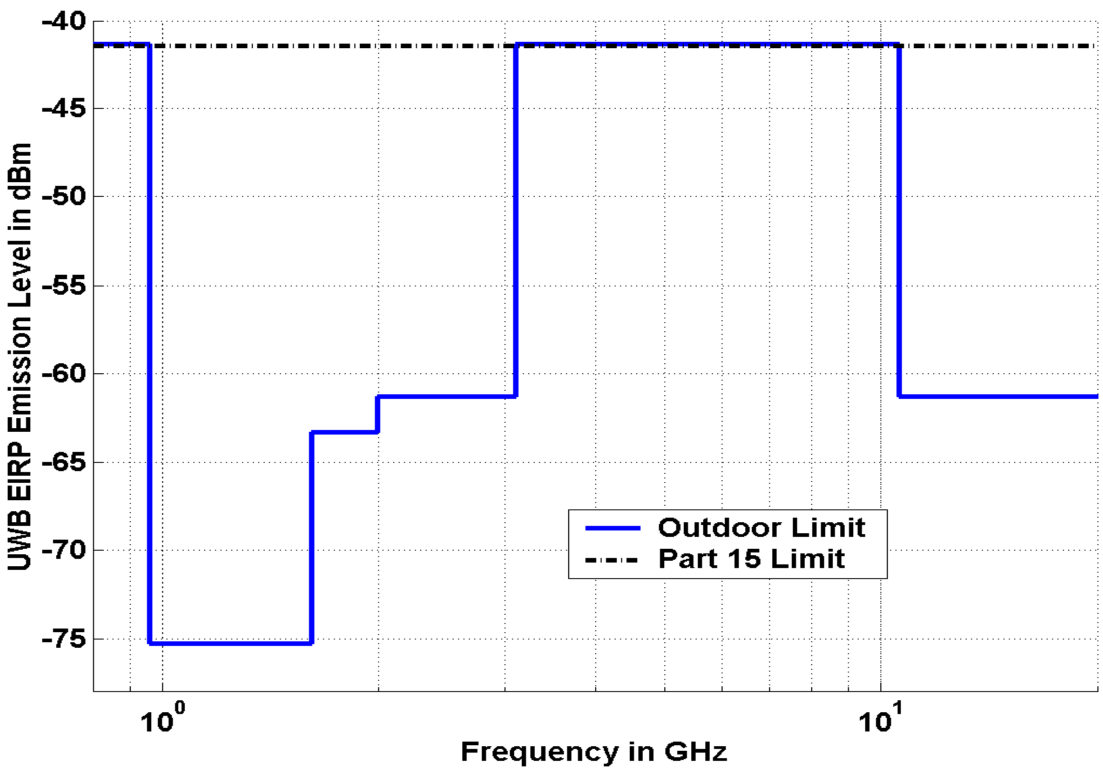
UWB (Ultra Wideband) Communication System

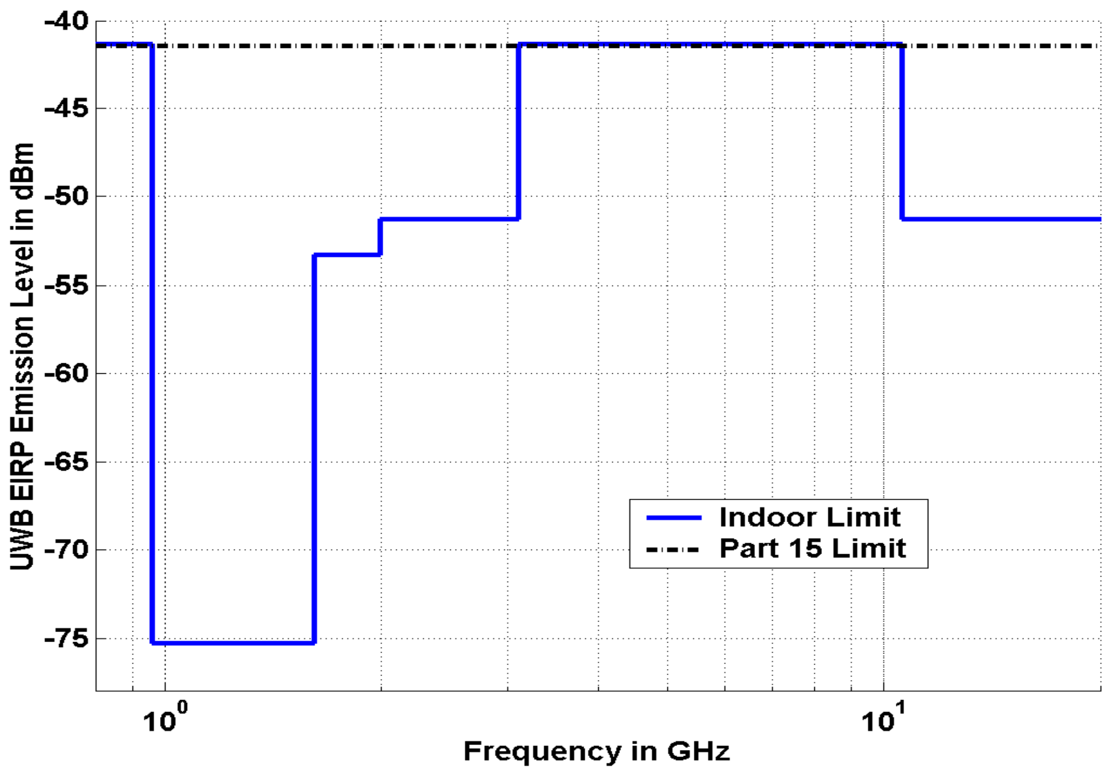
What is UltraWideBand?

- FCC: bandwidth is more than 25% of a center frequency or more than 1.5 GHz
- Typically implemented in a carrier-less fashion (Base-band modulation)
  - Directly modulate an “impulse” with a very sharp rise and fall time => a waveform that occupies several GHz.
- Historically started with radar applications for military use

FCC UWB Emission Limit for Outdoor Handheld Systems



FCC UWB Emission Limit For Indoor Systems



Information Modulation (continued)

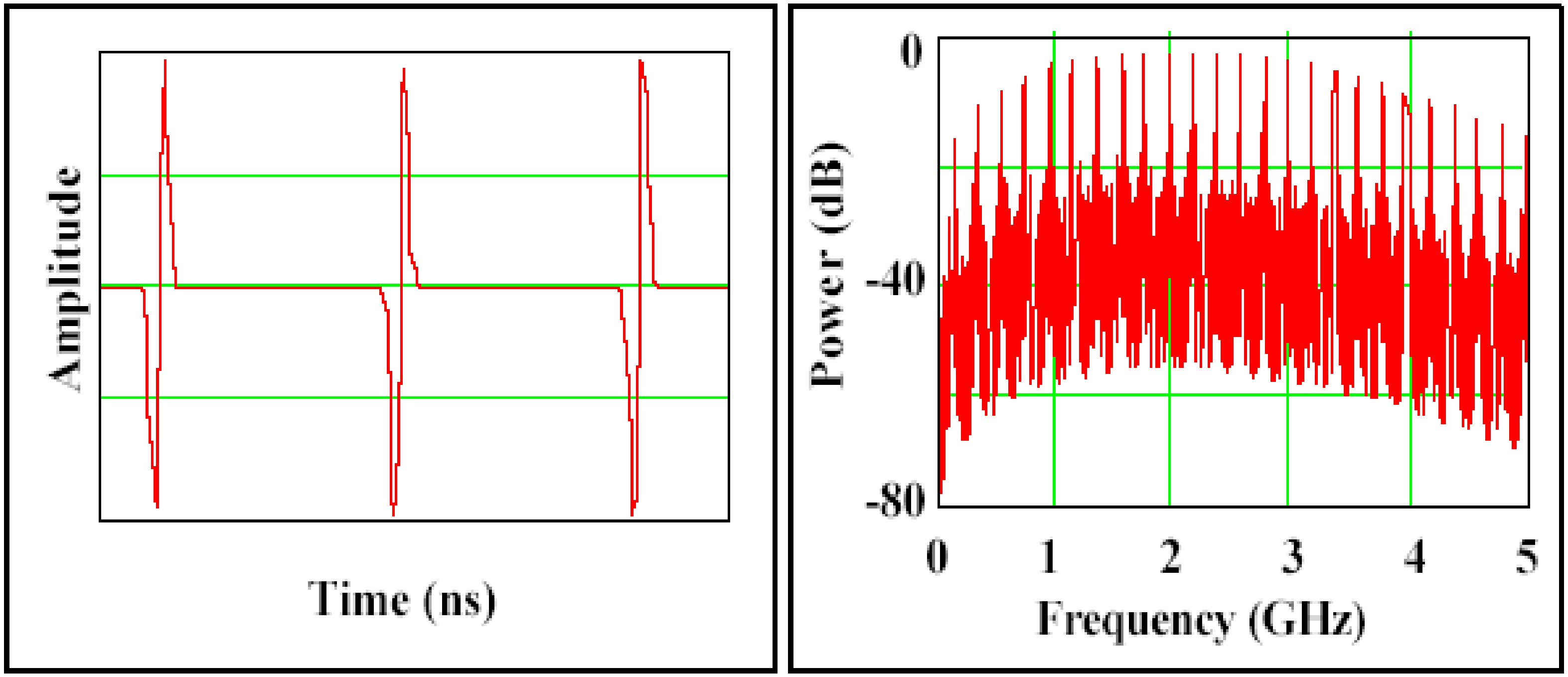


Figure 2. A Monocycle Pulse Train In The Time and Frequency Domains

Theoretical Motivation

- Shannon Channel Capacity Theorem
  - Capacity grows faster as a function of bandwidth than as a function of power

$$C = B \log_2 \left(1 + \frac{P}{BN_0}\right)$$

Where:
C = Channel Capacity (bits/sec)
B = Channel Bandwidth (Hz)
P = Received Signal Power (watts)
N_0 = Noise Power Spectral Density (watts/Hz)

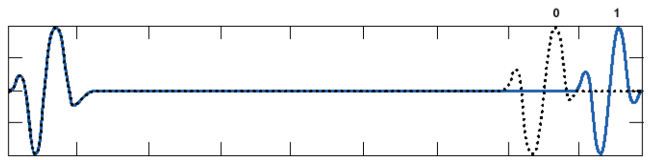
C is an increasing function of B

Capacity of a Gaussian Channel

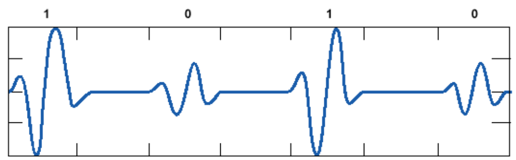
Information Modulation

Pulse length <1ns; Energy concentrated in 2-6GHz band; Power < 10uW

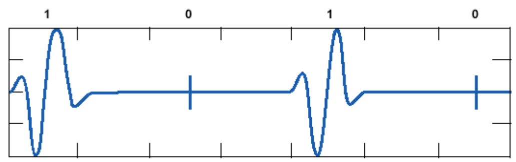
- Pulse Position Modulation (PPM)



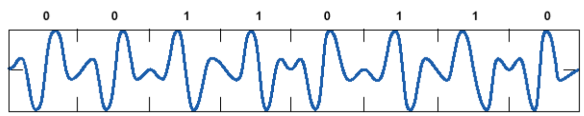
- Pulse Amplitude Modulation (PAM)



- On-Off Keying (OOK)



- Bi-Phase Modulation (BPSK)



Why is UWB attractive?

1. Simplicity: it's essentially a base-band system (carrier-free), for which the analog front-end complexity is far less than for a traditional sinusoidal radio.
2. High spatial capacity (bps/m^2)
3. Low power

   (Bluetooth:1Mbps,10m,1mW   UWB: 1Mbps,10m,10µW)
4. Low cost, simple implementation
5. Immune to multipath fading as well as multi-user interference

Two main data modulation schemes used for UWB systems

- Time hopping pulse position modulation (TH-PPM)

- Direct spread code division multiple access (DS-CDMA)

Basic Transmitter Model For TH-PPM

- Transmitter Model with typical time hopping format with Pulse-Position Modulation (PPM):
  - Step 1: Define monocycle waveform

$$s^{(k)}(t) = \sum_j w(t)$$

    - $S^{(k)}$ is the k^{th} transmitted signal
    - w(t) represents the transmitted monocycle waveform
  - Step 2: Shift to the beginning of Time frame

$$s^{(k)}(t) = \sum_j w(t - jT_f)$$

    - Tf is the pulse repetition time or frame time
    - j is the j th monocycle that sits at the beginning of each time frame.

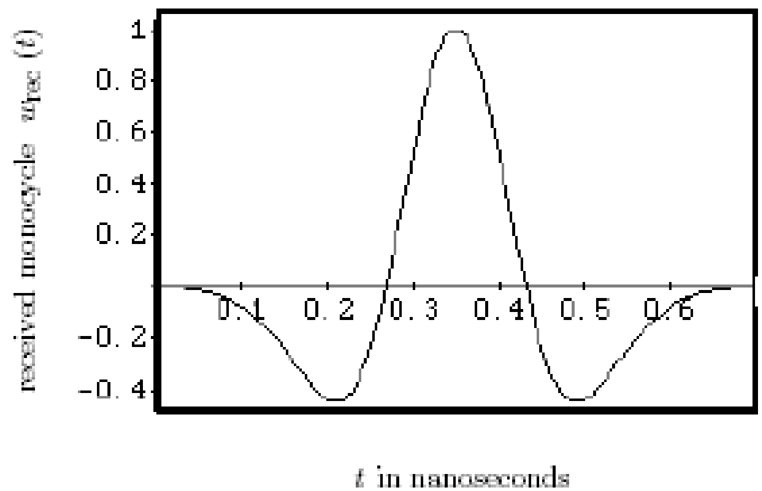


Figure 7.1 A typical received monocycle $w_{\text{rec}}(t)$ at the output of the antenna subsystem as a function of time in nanoseconds.

- Step 3 – Pseudorandom Time Hopping

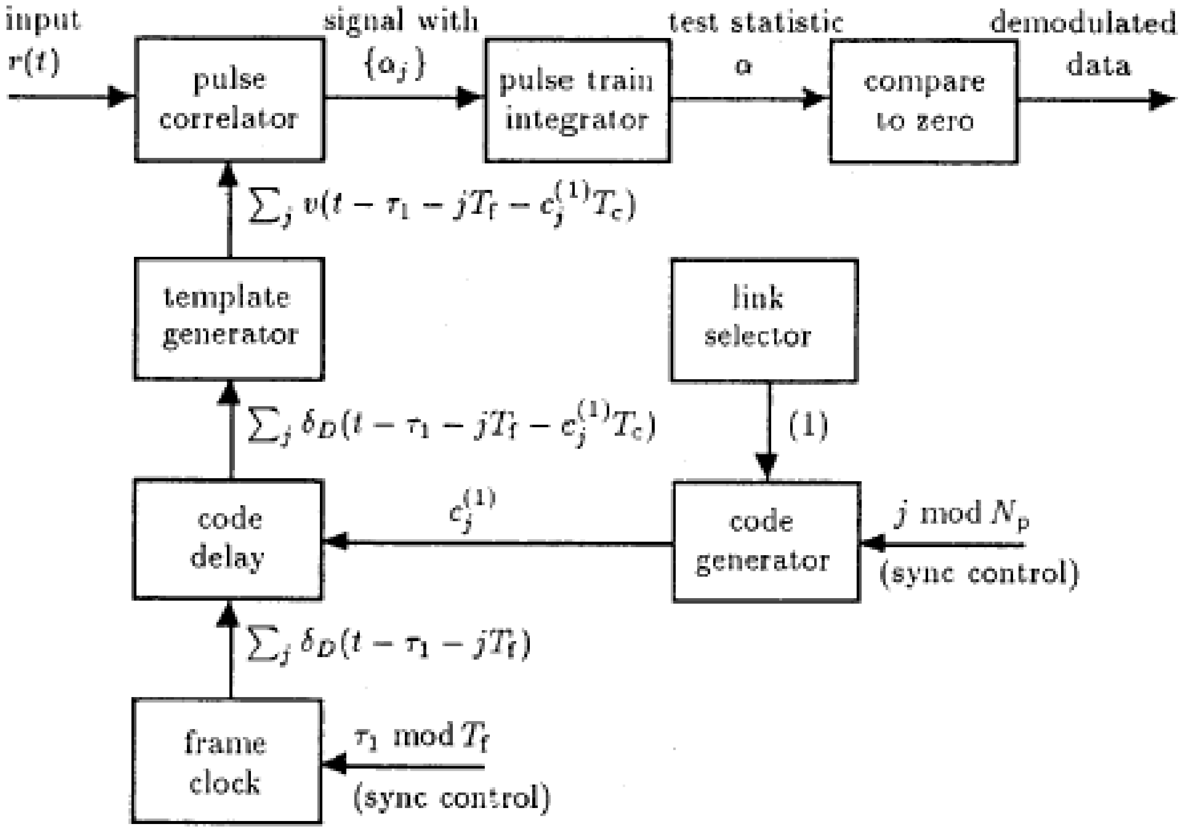
$$s^{(k)}(t) = \sum_j w(t - jT_f - c_j^{(k)} T_c)$$

  - To eliminate catastrophic collisions in multiple accessing
  - $\{C_j^{(k)}\}$ are time hopping code, periodic pseudorandom codes
  - T_c is the additional time delay that associate with the time hopping code
- Step 4 – Data Modulation

$$s^{(k)}(t) = \sum_j w(t - jT_f - c_j^{(k)} T_c - \delta d_{[j/N_s]}^{(k)})$$

  - $\{d_j^{(k)}\}$ is the primary data sequence of the transmitter
  - Data are transmitted every Ns monocycles per symbol
  - The symbol δ is the time shift that applies to the monocycle, and we define such operation happens when 1 is transmitted.

Receiver Block Diagram for the reception of the first user's signal



Receiver Model

- Signal at Receiver

$$r(t) = \sum_{k=1}^{Nu} A_k s^{(k)}(t - \tau_k) + n(t)$$

  - $A_k s^{(k)}$ models the attenuation of transmitter k's signal
  - N(t) is the white Gaussian noise
  - tau_k is time asynchronisms between clocks of transmitter and the receiver

- Correlation template signal

$$v(t) = w(t) - w(t - \delta)$$

  - V(t) is the pulse shape defined as the difference between two pulses shifted by the modulation parameter δ. It will then be correlated with the received signal for a statistical test

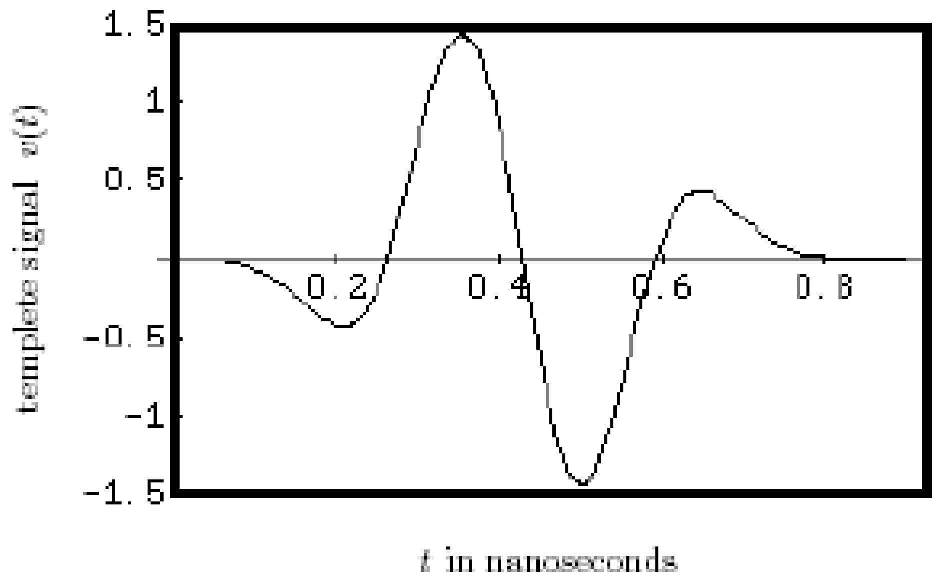


Figure 7.2 The template signal $v(t)$ with the modulation parameter δ chosen to be 0.156 ns. Since the template is a difference of two pulses shifted by δ, the non-zero extent of the template signal is approximately δ plus the monocycle width, i.e., about 0.86 ns.

- The optimal decision rule (one monocycle)

$$\mathrm{H}_0 \Leftrightarrow \int_{t \in T_i} r(t) v_{bit}(t - jT_f - c_j^{(k)} T_c) dt > 0$$

  - Pulse correlator output = α_j

$$\mathrm{H}_0 \Leftrightarrow \sum_{j=0}^{Ns-1} \int_{\tau_1 + jT_f}^{\tau_1 + (j+1)T_f} r(t) v_{bit}(t - jT_f - c_j^{(k)} T_c) dt > 0$$

  - Test statistic = α (one symbol)
  - if α >0 , the symbol transmitted is 0, else it is 1

Implementation of Time shift-keyed Equicorrelated (EC) signal sets for UWB TH_PPM M-ary modulation

- What is EC signal sets?
- Generating EC sequences.
  - The simplest method is using Hadamard matrix and removing first row and column with constraining number of frames per bit to be 2^m-1,p,p(p+2) (p is prime number)
  - Each row is an a sequence of bits corresponding to one of the M symbols
- the modulated signal for 1 bit is represented by

$$s(t) = \sum_{k=0}^{N_s-1} p(t - kTf - b_j{}^k \tau_2), i = 1,2,\ldots,M$$

EC signal sets parameters

- τ_2 is the time delay that corresponds to the minimum autocorrelation between p(t) and p(t- τ_2).
- The correlation of the EC signals is given by:

$$\lambda = \frac{\frac{N_s-1}{2}\gamma_w(0) + \frac{N_s+1}{2}\gamma_w(\tau_2)}{N_s}.$$

$$\lambda \approx \frac{1+\gamma_w(\tau_2)}{2}.$$

Receiver Simplification using EC signals

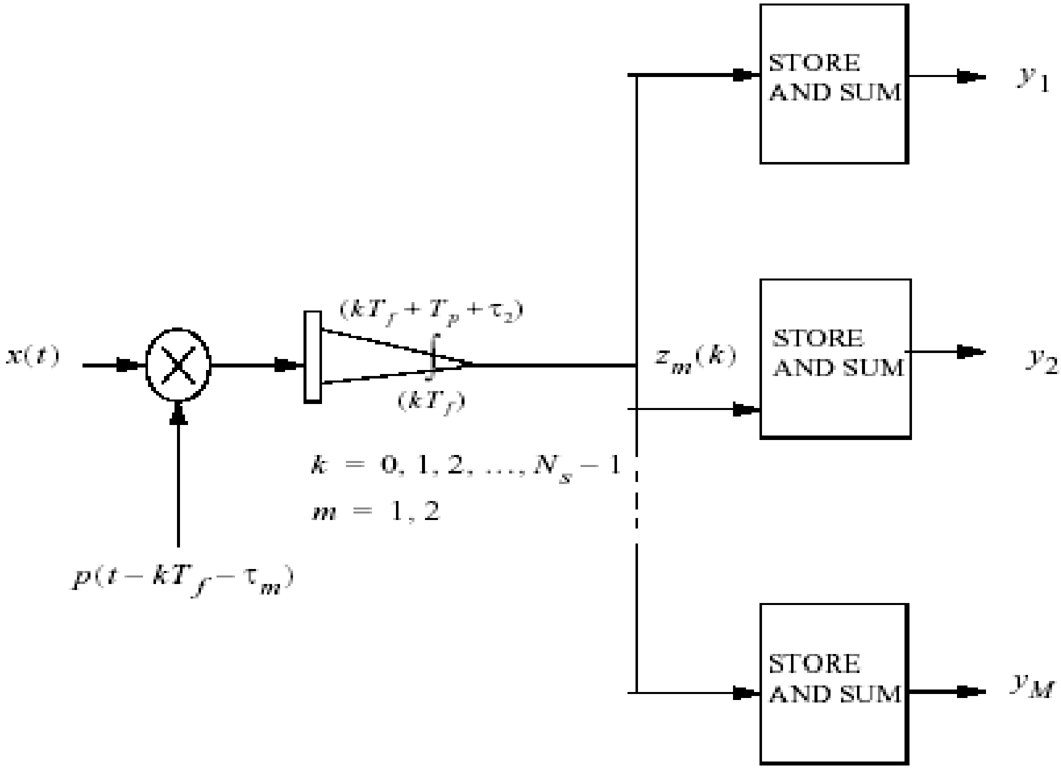
- Instead of using M correlators for each user, by using the properties of the EC signals, the receiver can be simplified to the use of two correlators and M store and sum circuits , the function is given by:

$$y_j = \sum_{k=0}^{N_s-1} \left[(b_j^k - 1) z_1(k) + b_j^k z_2(k) \right],$$

where

$$z_m(k) \triangleq \int_{kT_f}^{kT_f+T_p+\tau_2} x(t) p(t - kT_f - \tau_m) dt, \quad m = 1, 2.$$

Receiver Schematic (1 correlator)



Multi access performance limits for EC signals

- Degradation factor as a function of the number of users:

$$\mathrm{DF}(N_u) = \frac{1}{1 - \mathbf{SNRb}_{\mathrm{spec}} \left[\frac{1}{R_b} \frac{\mu / T_f}{(N_u - 1)} \right]^{-1}}.$$

- Maximum bit transmission rate:

$$R_{\max} \triangleq \lim_{\mathrm{DF} \to \infty} N_u(\mathrm{DF}) = \frac{1}{\mathbf{SNRb}_{\mathrm{spec}}} \frac{1}{N_u - 1} \frac{\mu}{T_f}.$$

Multi access performance limits for EC signals (cont.)

- Maximum Number of users:

$$N_{\max} \triangleq \lim_{\mathrm{DF}\to\infty} N_u(\mathrm{DF}) = \frac{1}{\mathbf{SNRb}_{\mathrm{spec}}} \frac{1}{R_b} \frac{\mu}{T_f} + 1.$$

- The multiple-access transmission capacity:

$$C(B) \simeq \frac{1}{\log(2)} \frac{\mu/T_f}{N_u - 1} = C_{\mathrm{IR}}(N_u)$$

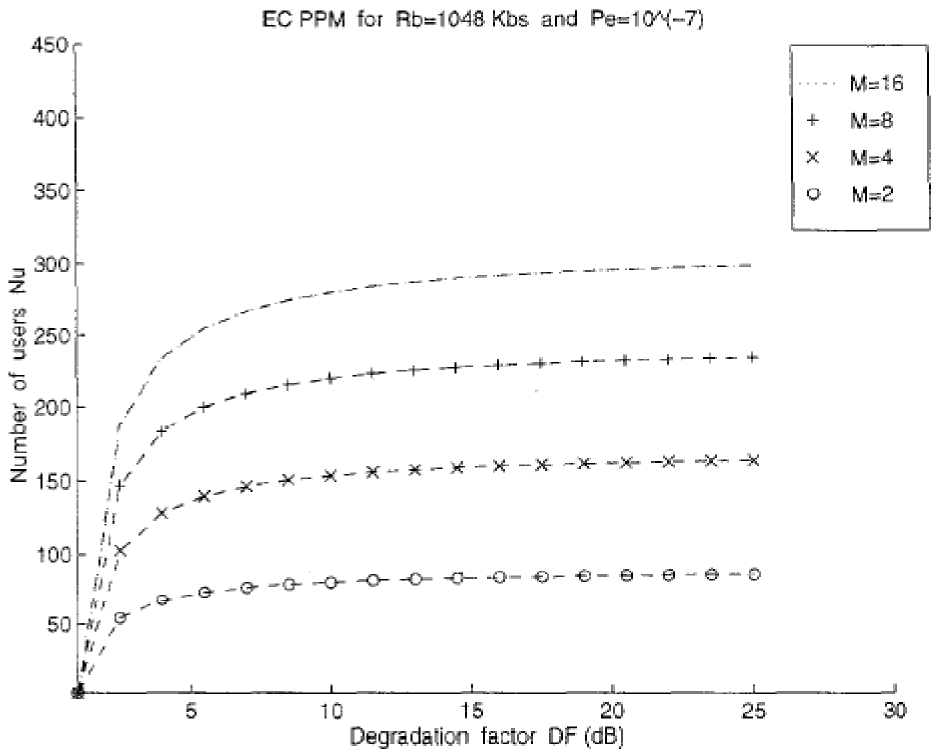
- where:

$$\mu = \frac{(E_w[1-\gamma_w(\tau_2)])^2}{2\sigma_a^2} \qquad \sigma_a^2 = \frac{1}{T_f}\int_{-\infty}^{\infty}\left[\int_{-\infty}^{\infty} w(t-s)[w(t)-w(t-\tau_2)]dt\right]^2 ds,$$

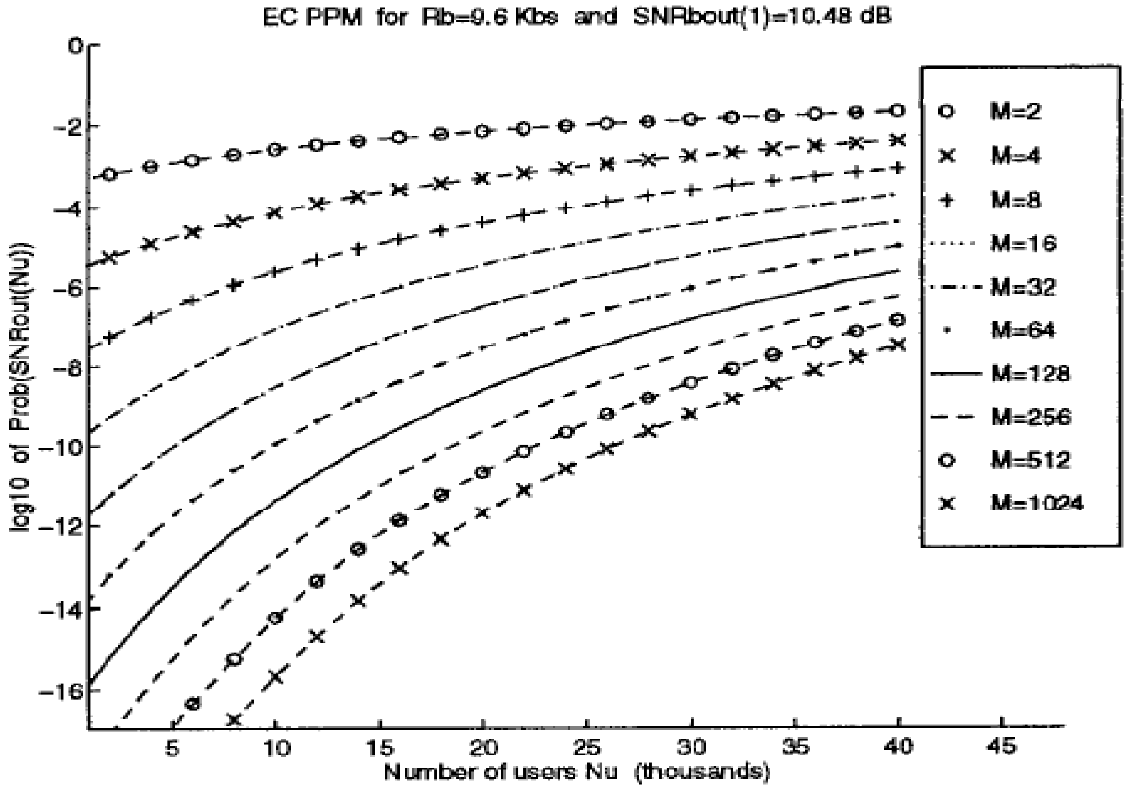
where SNRb_{spec} is the specified operating snr to achieve the desired probability of error

Degradation Factor

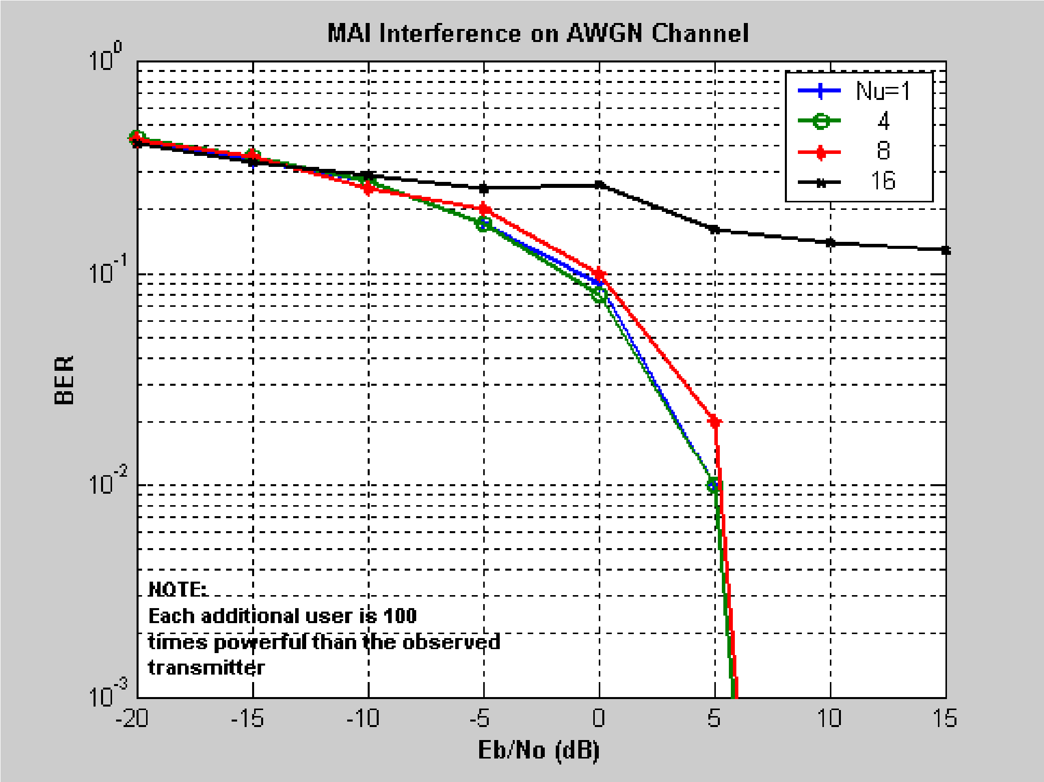
- Degradation Factor is the additional amount of Snr required by user 1 to overcame the MAI:

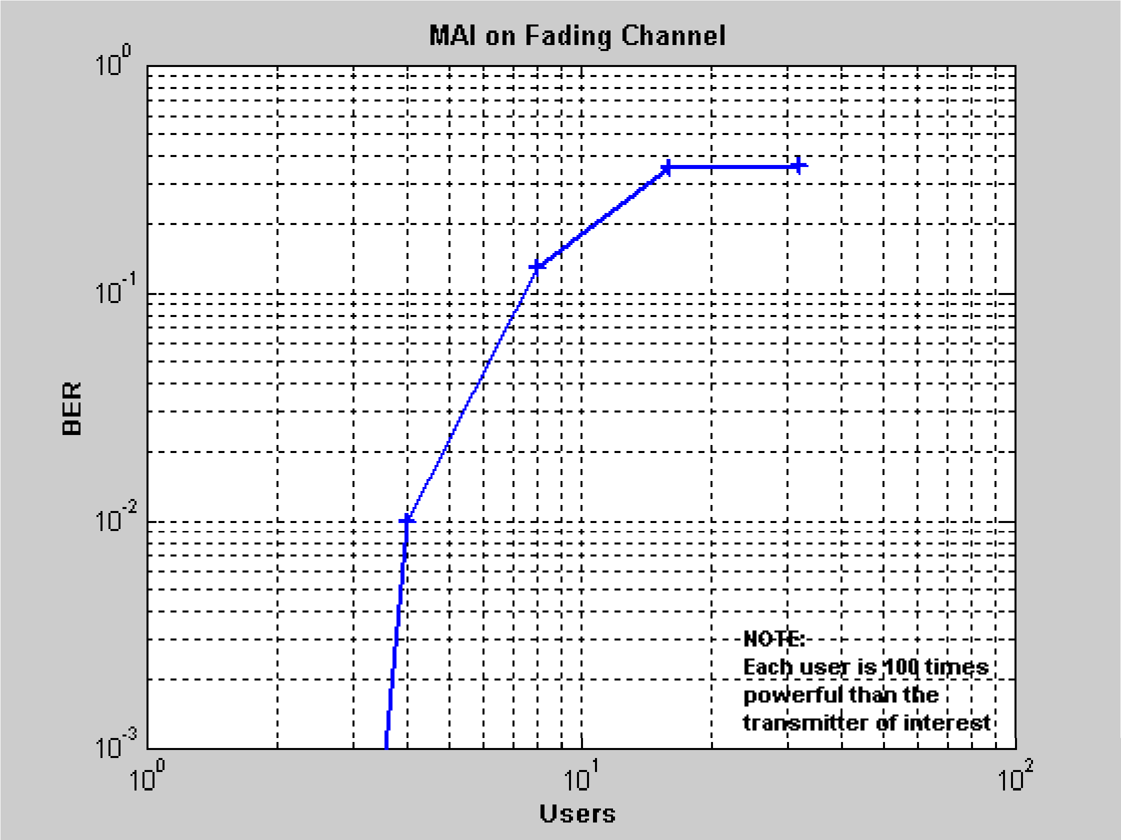


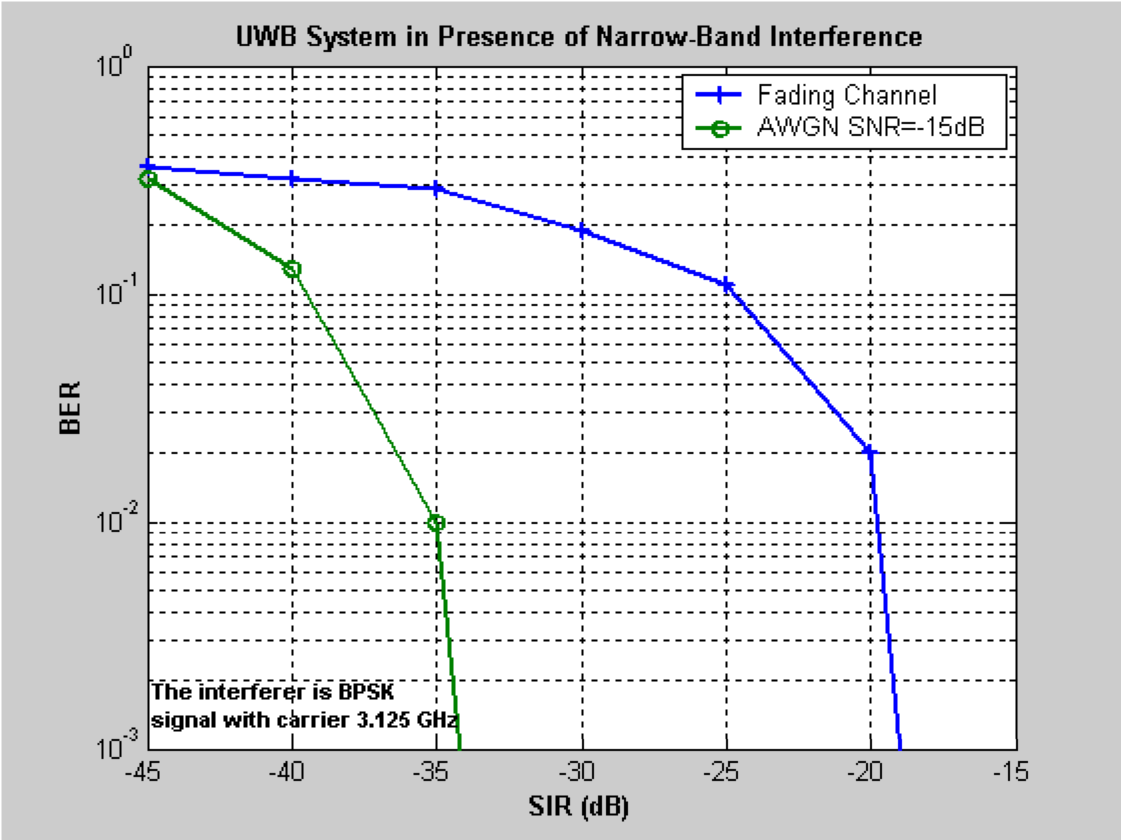
Behavior of the prob(SNR(out)) as a function of Number of users



Simulation Results

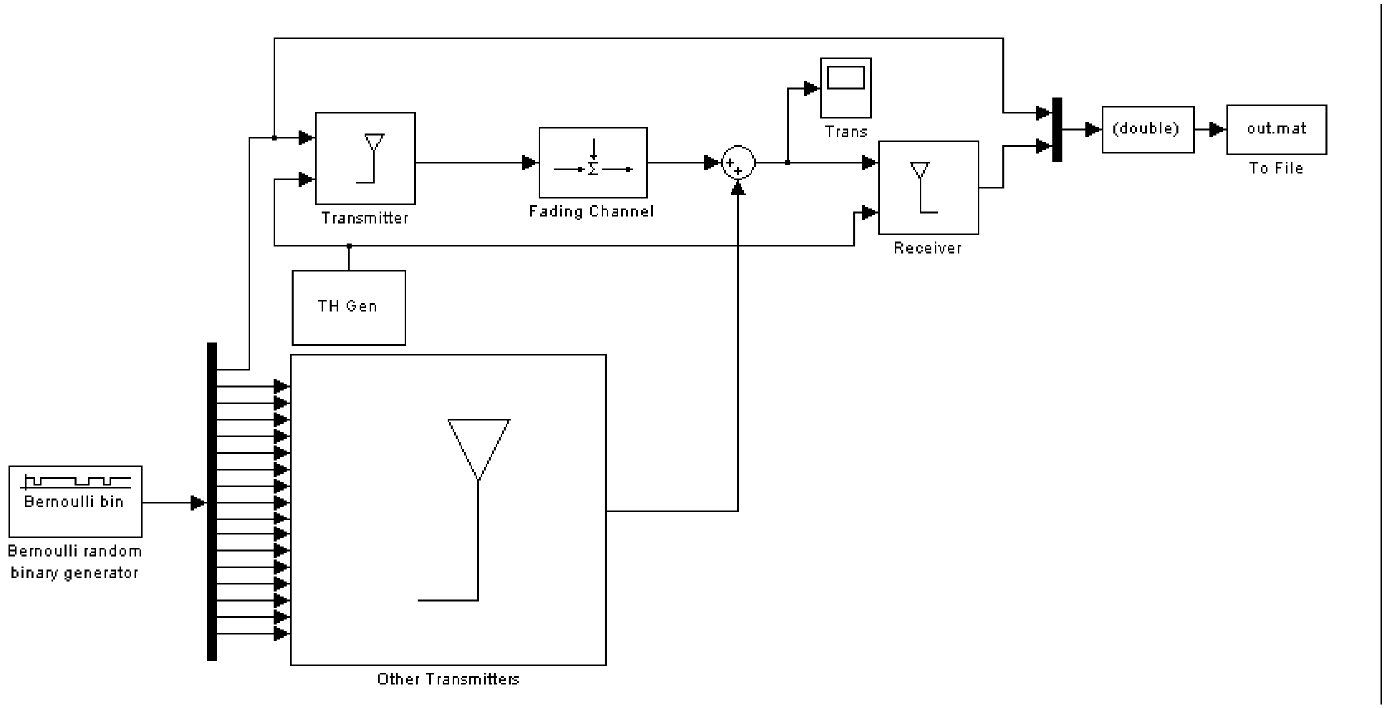



MAI on Fading Channel
10^0
10^{-1}
10^{-2}
10^{-3}
BER
10^0
10^1
10^2
Users
NOTE:
Each user is 100 times powerful than the transmitter of interest

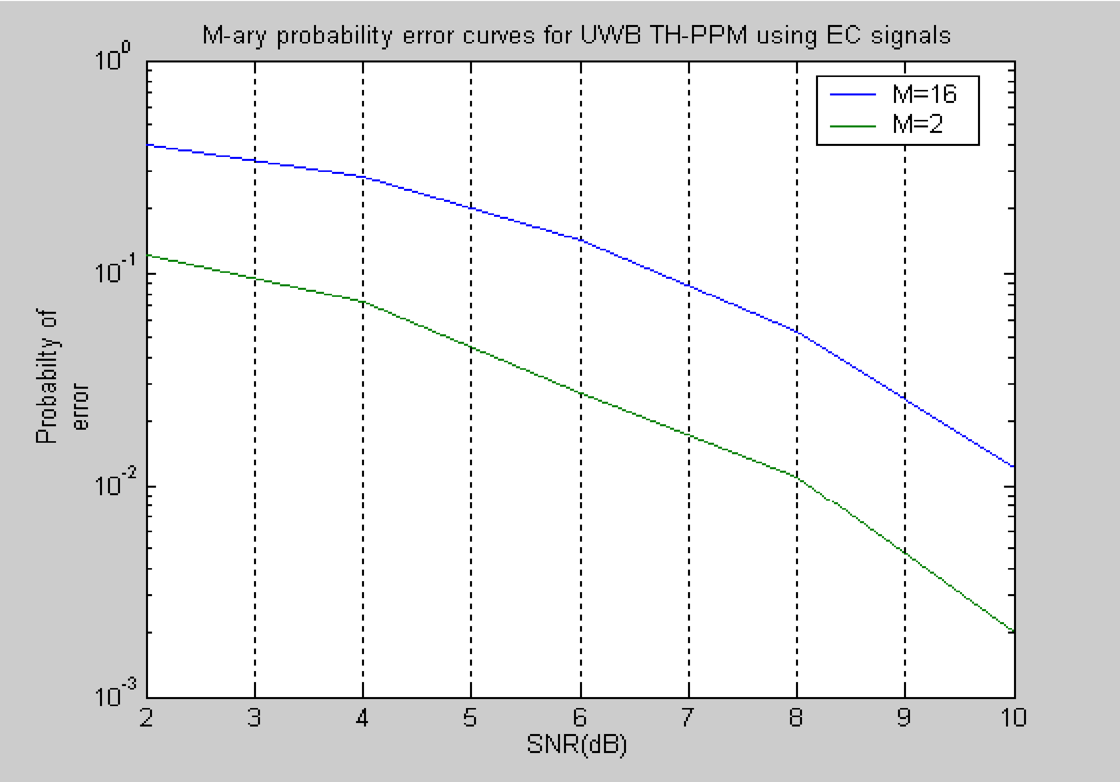


UWB System in Presence of Narrow-Band Interference
Fading Channel
AWGN SNR=-15dB
The interferer is BPSK
signal with carrier 3.125 GHz
BER
SIR (dB)
10^{0}
10^{-1}
10^{-2}
10^{-3}
-45
-40
-35
-30
-25
-20
-15

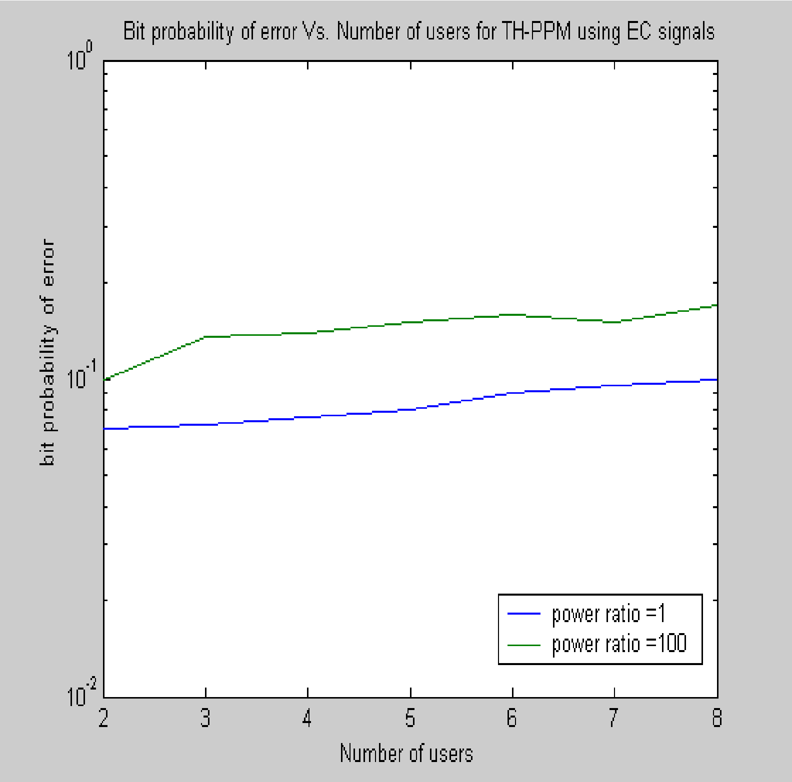
Model Example

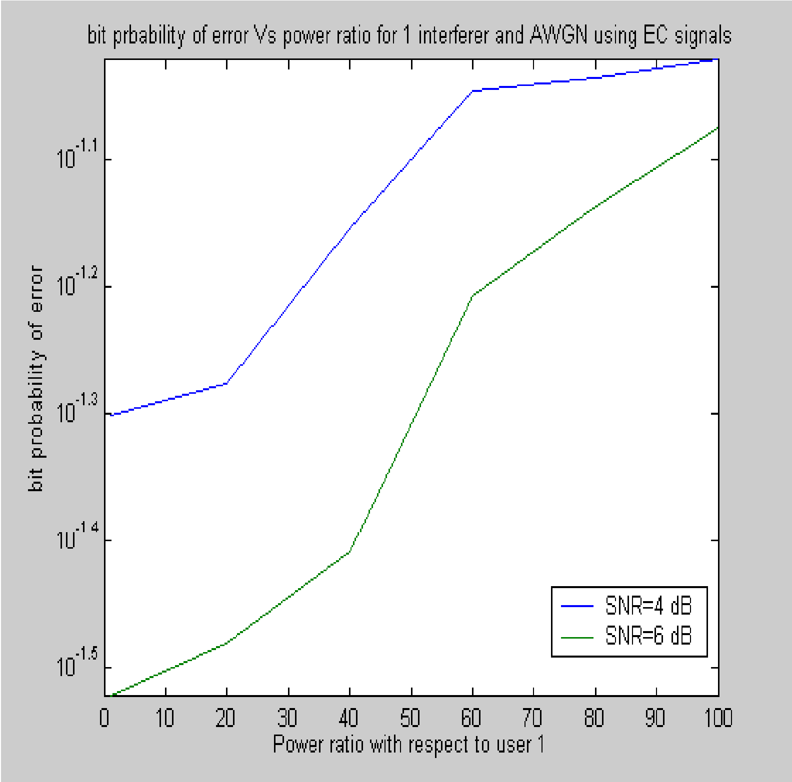


Bit error performance for M-ary UWB TH-PPM using EC signals



Multi user behavior of UWB TH-PPM using EC signals





Direct Sequence, DS-UWB

- Similar to conventional CDMA carrier based radios
- Spreading sequence is multiplied by an impulse sequence
- Modulation is provided as in CDMA

Basic signal model for UWB DS-CDMA

- Transmitted waveform is defined as,

$$s_k(t) = \sqrt{P_k} \sum_{i=-\infty}^{\infty} \sum_{n=0}^{N_r-1} b_i^k a_n^k z(t - iT_r - nT_c)$$

- Where z(t) is the transmitted monocycle waveform,
  - b_i^k are the modulated data symbols for the k^{th} user,
  - a_n^k are the spreading chips,
  - T_r is the bit period, T_c is the chip period,
  - $N_r = T_r / T_c$ is the spread spectrum processing gain, and
  - P_k is the transmitted power

The Received signal

- r(t)=s(t) + M(t) +I(t)+ n(t)
- M(t) is the multiple access interference

$$M(t) = \sum_{k=1}^{K} \sum_{i=-\infty}^{\infty} \sum_{n=0}^{Nr-1} b_i^k a_n^k z(t - iTr - nTc - \tau_k) \qquad 0 \le \tau_k < T_r .$$

- I(t) is the narrow band interference

assuming raised cosine wave

- The receiver is correlator

DS-CDMA simulation

- Binary spreading
- Ternary spreading

Episodic Transmission (Ternary Spreading)

- Send n pulses for per information bit
- Allow for off time separation
- Modeled as random ternary with pmf,

$$p_b(b_i) = (1-2\alpha)\delta(b_i) + \alpha \cdot \delta(b_i - 1) + \alpha \cdot \delta(b_i + 1)$$

- Chernoff Bound on the probability of bit error,
- $P_e < \exp\left(\frac{-n\mathcal{E}_k}{2I_0}\right)$ where ε is the chip energy,

$$I_0 = \sigma_v^2 + 2\alpha \sum_{\substack{j=1 \\ j \neq k}}^{K} \mathcal{E}_j$$

K is the number of users,

σ_v^2 is the AWGN variance

Ternary Spreading Cont,

- As α becomes smaller, MUI may be significantly reduced (with a corresponding reduction in bit rate)
- Demonstrate the performance of such a sequence by using ternary sequences with aperiodic zero correlation zones (ZCZ).

ZCZ Sequences

- These are the sequences which have a zero valued window around the zero shift, in the autocorrelation (AC) and crosscorrelation (CC) function.

- $Z_{CZ} = \min \{Z_{ACZ}, Z_{CCZ}\}$

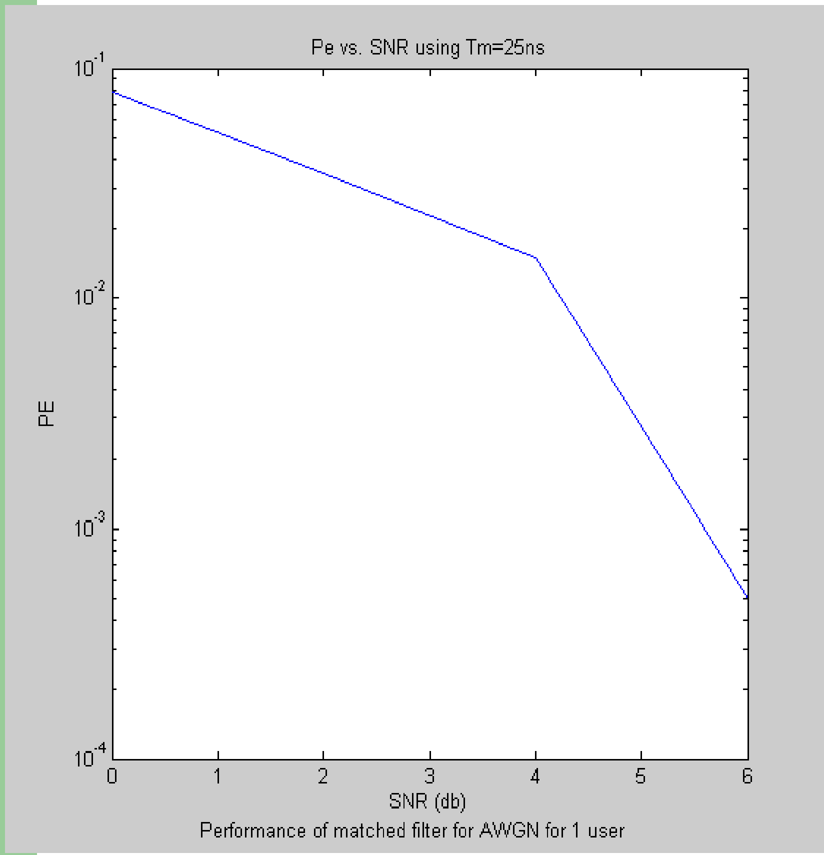
- Interference between users separated by delays that are within this window or interference due to delayed replicas of a users signal due to the multipath channel will be eliminated.

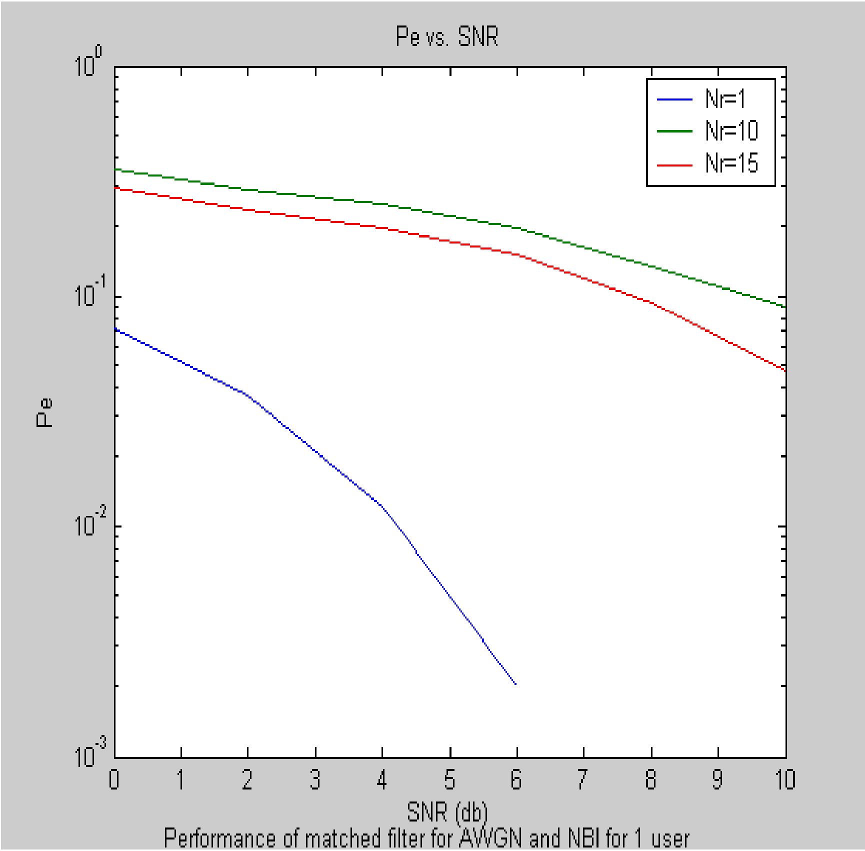
A simple way to create ternary ZCZ sequences

- Take M orthogonal binary sets
- Insert zero padding of length Z_0 between the elements of the sets
- Shift each subset a different number of chips

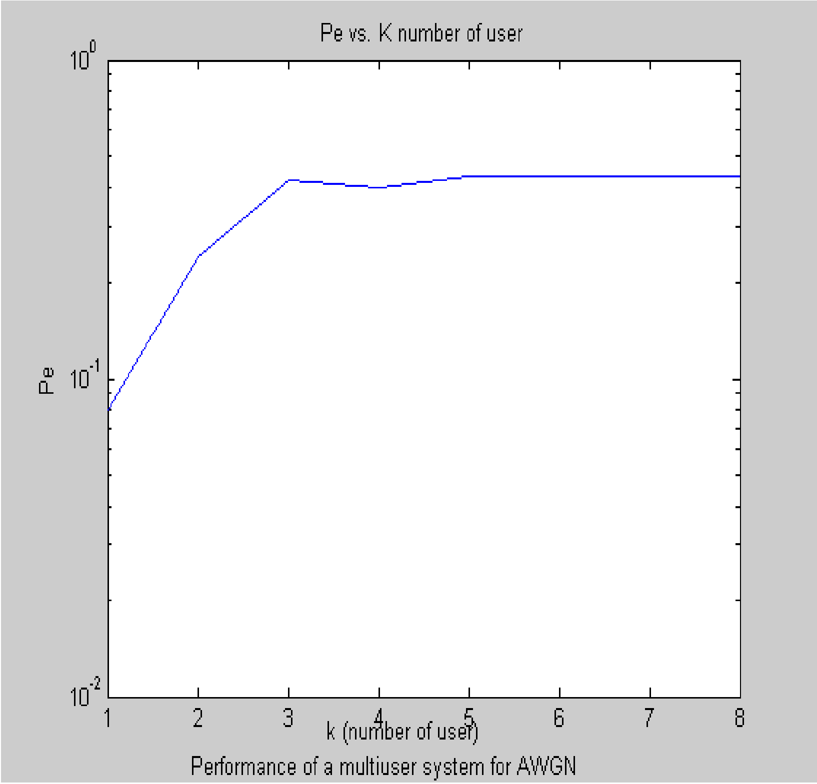
$$
\begin{array}{l}
s_1 \Rightarrow \begin{bmatrix} +++- \\ ++-+ \\ +-++ \\ +--- \end{bmatrix} \Rightarrow S_1(\tau_1) \Rightarrow \\
s_2 \Rightarrow \begin{bmatrix} ++++ \\ +-+- \\ ++-- \\ +--+ \end{bmatrix} \Rightarrow S_2(\tau 2) \Rightarrow
\end{array}
\quad
P_2 = \left\{ \begin{array}{l}
\begin{bmatrix} 000+000+000+000- \\ 000+000+000-000+ \\ 000+000-000+000+ \\ 000+000-000-000- \end{bmatrix} \\
\begin{bmatrix} 0+000+000+000+00 \\ 0+000-000+000-00 \\ 0+000+000-000-00 \\ 0+000-000-000+00 \end{bmatrix}
\end{array} \right\}
$$

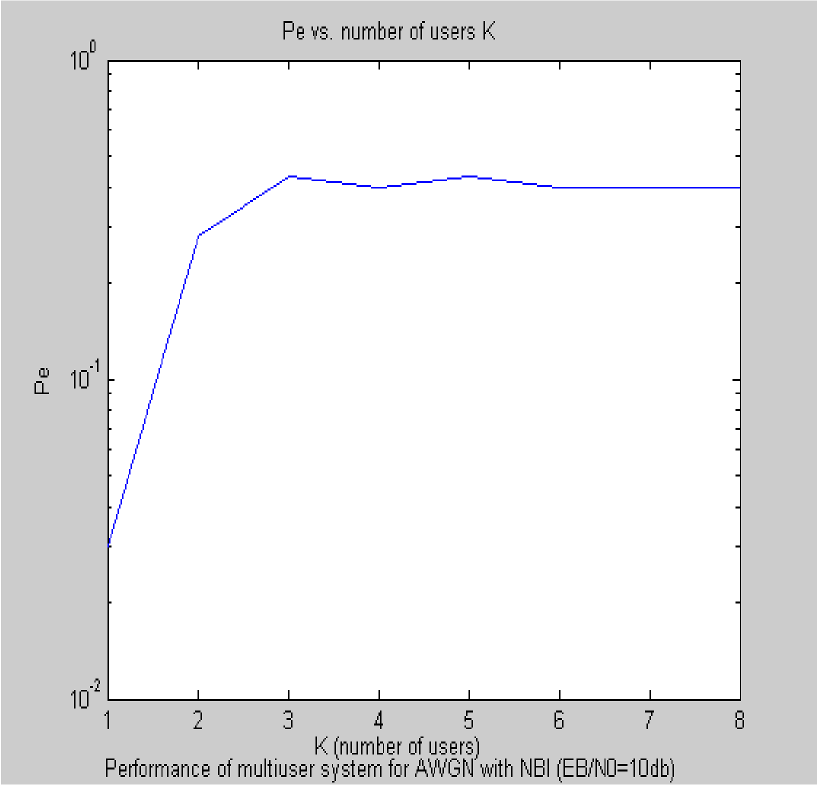
The performance of one user system for Binary DS-UWB (AWGN and NB Interference)



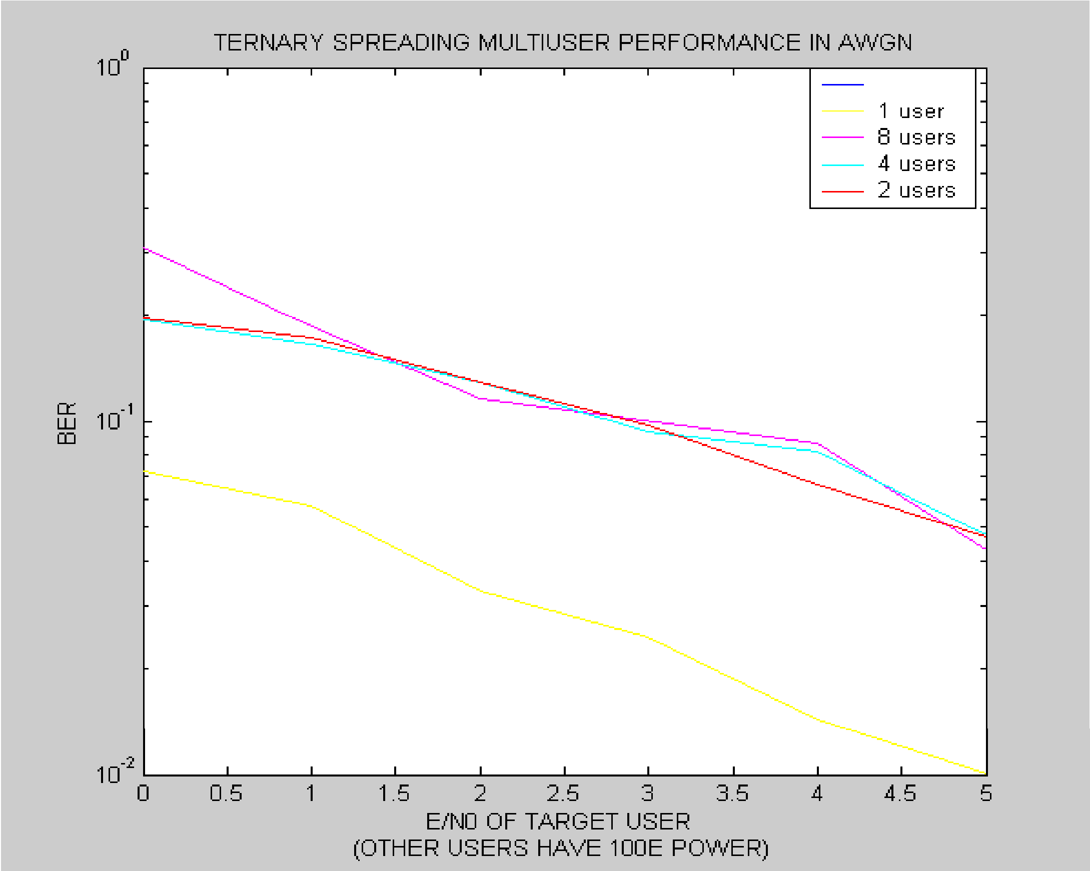


Multiuser performance of Binary DS-UWB (1-8 users, AWGN & NB Interference)

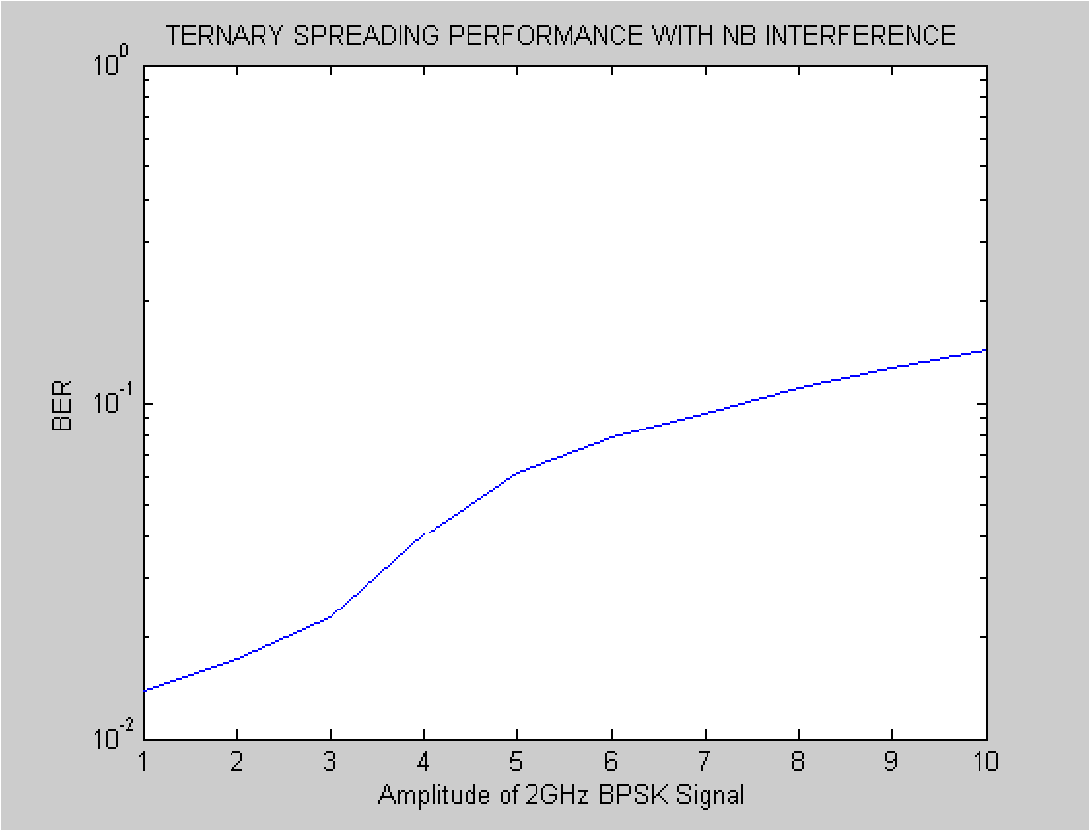




Ternary Spreading Multiuser Performance in AWGN (69Mbit/s)



Performance of 1 watt Ternary DS-UWB with NBI (69Mbit/s, SNR=7dB)



Conclusion

- By using EC signals in TH-PPM with large values of M it is possible to increase number of users supported by the system for given multiple access performance and bit transmission rate.
- The analysis shows that impulse radio using TH-PPM is potentially able to provide multiple-access communications with combined transmission capacity of over 500 Mbps at bit error rate in the range of 10^{-4} to 10^{-8}
- The graphs shows that UWB CDMA reduces the impact of the multi-user interference
- Increasing the number of users does not affect the probability of error as it should be for any other system