

# Performance Characterization of UWB SSMA Using Orthogonal PPM-TH in Dense Multipath

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**Abstract.** In this work we study ultra wideband (UWB) communications over dense multipath channels using orthogonal pulse position modulation (PPM) for data modulation and time-hopping (TH) for code modulation. We consider the effects of the multiple access interference (MUI) in asynchronous spread spectrum multiple access (SSMA) based on random TH codes. We consider a realistic multipath channel to analyze the effects of the transmission rate in the number of users for different bit error rate (BER) values.

**Keywords:** Ultra wideband communications, pulse position modulation, multipath channels, spread spectrum multiple access.

## 1 Introduction

The UWB communications for short-range high-speed wireless communications has been studied extensively [1]-[7]. This work studies the performance of binary UWB communications in the presence of additive white Gaussian noise (AWGN), MUI, and dense multipath effects (DME). Several authors have studied this problem before.

The work in [8] studied an *all-digital* receiver using time hopping with binary pulse amplitude modulation and synchronous time-division duplexing, with a multipath channel model that assumes the path arrival times being uniformly distributed over the delay spread span and the amplitude of each path being Gaussian decaying linearly with delay, and with the maximum delay spread fixed to a certain constant value.

The work in [9] studied a *digital* receiver using TH combined with orthogonal binary PPM including *multi-stage block-spreading* to cancel MUI deterministically, with the channel modeled with a finite impulse response filter of fixed order that includes asynchronisms in the form of delay factors and frequency selective multipath effects.

The work in [10] used a signal-to-interference analysis to study the degradation factor due to MUI in the presence of DME when using binary PPM-TH signals, with a multipath model assuming path arrival times uniformly distributed

over one frame period with special cases of exponentially decaying and flat amplitude profiles.

In [11] the error probability of UWB SSMA using TH combined with binary PPM is studied in the presence of interference and multipath, comparing performance for different modulation schemes, interference conditions, and receivers types.

In [12] a closed-form expression of the MUI variance in multipath channel for binary pulse amplitude modulation and time hopping PAM-TH was found.

In this work we use a simple expression for the BER [13] and consider a realistic multipath indoor office channel using the Time Domain Corporation Indoor Channel Database to analyze the effects of the transmission rate in the number of users for different BER values.

## 2 System Model

### 2.1 Transmitted Signals

The *transmitted* signal is described by

$$\Psi_{\text{TX}}^{(\nu)}(t) = \sum_{k=0}^{N_s-1} p_{\text{TX}}(t - kT_f - c_k^{(\nu)}T_c - b_j\delta), \quad (1)$$

where  $t$  denotes time, the index  $k$  is the number of time hops that the signal  $\Psi_{\text{TX}}^{(\nu)}(t)$  has experienced,  $T_f$  is the average frame time between pulse transmissions, and  $p_{\text{TX}}(t)$  is the UWB pulse used to build the transmitted PPM signals.

The superscript  $1 \leq \nu \leq N_u$ , indicates user-dependent quantities, Without loss of generality, we will assume that user one is the desired user.

The  $b_j$  is the  $j^{\text{th}}$  data bit,  $j = 1, 2$ , taking one of two equally likely values from the binary set  $\{0, 1\}$ . The time shift value  $\delta$  is chosen such that set of signals are orthogonal in the absence of multipath.

For a given time shift parameter  $T_c$ , the pseudo-random TH code  $\{c_k^{(\nu)}\}$  provides an additional time shift to the pulse in every frame, each time shift being a discrete time value  $c_k^{(\nu)}T_c$ , with  $0 \leq c_k^{(\nu)}T_c < N_hT_c$ . The data bit changes only every  $N_s$  hops, i.e., the system uses fast time hopping.

The UWB pulse  $p_{\text{TX}}(t)$  is the basic signal used to convey information. This pulse is characterized by a radiated spectrum with a very wide bandwidth (a few Giga Hertz) around a relatively low center frequency (one or two Gigahertz). The duration of the pulse  $T_p$  is in the order of a few nanoseconds.<sup>1</sup>

<sup>1</sup> As defined by the Federal Communications Commission (FCC) of the United States, any signal is of UWB nature when it has a 10 dB bandwidth of at least 500 MHz, or when its fractional bandwidth (the ratio of the 10 dB bandwidth to the central frequency) is at least 20 percent [14].

## 2.2 Model for the Gaussian Channel

Under free space propagation conditions the received signal

$$\Psi^{(\nu)}(t) = \sum_{k=0}^{N_s-1} p(t - kT_f - c_k^{(\nu)}T_c - b_j\delta) \quad (2)$$

is modeled as the derivative of the transmitted signal  $\Psi_{\text{TX}}^{(\nu)}(t)$ .<sup>2</sup> The received signal is modified by amplitude  $A_o$  and delay  $\tau_o$  factors that depend on the transmitter-receiver separation distance (in our analysis we will assume  $A_o = 1$  and  $\tau_o = 0$ ).

The signals  $\Psi^{(\nu)}(t)$  in (2) have duration  $T_s = N_sT_f$  and energy

$$E_{\Psi} \triangleq \int_{-\infty}^{\infty} [\Psi^{(\nu)}(t)]^2 dt = N_s E_p, \quad (3)$$

for  $j = 1, 2$ , where  $E_p = \int_{-\infty}^{\infty} [p(t)]^2 dt$  is the energy of the *received* UWB pulse  $p(t)$ . The signals  $\Psi^{(\nu)}(t)$  have normalized correlation values

$$\beta \triangleq \frac{\int_{-\infty}^{\infty} \Psi_{j_1}^{(\nu)}(t) \Psi_{j_2}^{(\nu)}(t) dt}{E_{\Psi}} = \begin{cases} 1, & j_1 = j_2, \\ \gamma(\delta), & j_1 \neq j_2, \end{cases} \quad (4)$$

where

$$\gamma(\delta) \triangleq \frac{\int_{-\infty}^{\infty} p(t) p(t - \delta) dt}{E_p} \quad (5)$$

is the normalized autocorrelation function of  $p(t)$ . The time shift value  $\delta = 2T_p$  is chosen such that the signal correlation  $\gamma(\delta) = 0$ .

The noise at the receiver  $n(t)$  is AWGN with two-sided power spectrum density (PSD)  $N_o/2$ .

## 2.3 Model for the Multipath Channel

**Multiple-Path Trajectories** For each active link the corresponding transmitter stays fixed at certain arbitrary position, and the corresponding receiver moves in a spatially random fashion.

In particular, the link between user one's receiver and user  $\nu$ 's transmitter defines a multiple-path propagation trajectory that is a function of the relative position of user one's receiver with respect to the position of user  $\nu$ 's transmitter. This random trajectory will be identified with the random index  $\xi^{(\nu)}$ . There will be  $N_u$  of such trajectories, one for every pair (user  $\nu$ 's transmitter, user one receiver),  $\nu = 1, 2, \dots, N_u$ .

<sup>2</sup> This model for the antenna system has been repeatedly used [1]-[7]. Most existing UWB antennas do not have the differentiation effect. Even for those antennas systems, the analysis in this work still can be applied because it is based on the energy and correlation values of the *received* signals.

When user  $\nu$ 's transmitter radiates the signal  $p_{\text{Tx}}(t)$ , the signal detected by user one's receiver will be represented by  $p(\xi^{(\nu)}, t)$ . As we move user one's receiver position, these trajectories change. Hence, the received waveforms coming from each of the transmitters also change.

**Channel Effect in the UWB Pulse** In an indoor multipath channel, transmission of the pulse  $p_{\text{Tx}}(t)$  results in a received "pulse"  $\sqrt{E_a} p(\xi^{(\nu)}, t)$  which is a multipath spread version of  $p(t)$ . The average duration of  $p(\xi^{(\nu)}, t)$  is denoted  $T_a$ , and can be in the order of up to a few hundreds of nanosecond, hence  $T_a \gg T_p$ . We will assume that  $T_a$  is the equivalent of the mean delay spread of the channel.

The pulse  $\sqrt{E_a} p(\xi^{(1)}, t)$  has random energy  $E_p(\xi^{(1)}) \triangleq E_a \alpha^2(\xi^{(1)})$ , where  $E_a$  is the average received energy, and  $\alpha^2(\xi^{(1)}) \triangleq \int_{-\infty}^{\infty} [p(\xi^{(1)}, t)]^2 dt$  is the normalized random energy. The pulse has normalized random signal correlation

$$\gamma(\xi^{(1)}, \delta) \triangleq \frac{\int_{-\infty}^{\infty} p(\xi^{(1)}, t) p(\xi^{(1)}, t - \delta) dt}{\alpha^2(\xi^{(1)})}.$$

The normalized signal cross-correlation corresponding to pulses received with two different trajectories  $\xi^{(1)}$  and  $\xi^{(\nu)}$  is

$$\tilde{\gamma}(\xi^{(1)}, \xi^{(\nu)}, \delta) \triangleq \frac{\int_{-\infty}^{\infty} p(\xi^{(1)}, t) p(\xi^{(\nu)}, t - \delta) dt}{\tilde{\alpha}^2(\xi^{(1)}, \xi^{(\nu)})},$$

where  $\tilde{\alpha}^2(\xi^{(1)}, \xi^{(\nu)}) \triangleq \int_{-\infty}^{\infty} p(\xi^{(1)}, t) p(\xi^{(\nu)}, t) dt$ .

## 2.4 Model for the Multipath Channel

The PPM-TH signals received in the presence of multipath are

$$\Psi^{(\nu)}(\xi^{(\nu)}, t) = \sum_{k=0}^{N_s-1} \sqrt{E_a} p(\xi^{(\nu)}, t - kT_f - c_k^{(\nu)} T_c - b_j \delta). \quad (6)$$

The signal in (6) is received with trajectory  $\xi^{(\nu)}$ , and is a multipath spread version of the signal in (2).

Here we have assumed that the channel is slowly time invariant, therefore the PPM signal is composed of shifted version of the same spreaded pulse. We will further assume that  $\Psi^{(\nu)}(\xi^{(\nu)}, t)$  has fixed duration  $T_s \simeq N_s T_f$ .

The signals  $\Psi^{(1)}(\xi^{(1)}, t)$  have random energy

$$E_{\Psi}(\xi^{(1)}) = \int_{-\infty}^{\infty} [\Psi^{(1)}(\xi^{(1)}, t)]^2 dt \simeq \bar{E}_s \alpha^2(\xi^{(1)}), \quad (7)$$

where  $\bar{E}_s = N_s E_a$  is the average bit energy. The signals have normalized random correlation values

$$\beta(\xi^{(1)}) \triangleq \frac{\int_{-\infty}^{\infty} \Psi_{j_1}^{(1)}(\xi^{(1)}, t) \Psi_{j_2}^{(1)}(\xi^{(1)}, t) dt}{E_{\Psi}(\xi^{(1)})} = \begin{cases} 1, & j_1 = j_2, \\ \gamma(\xi^{(1)}, \delta), & j_1 \neq j_2, \end{cases} \quad (8)$$

## 2.5 The Case with Multiple-Users

In the system model under consideration all the users transmit the same type of binary time hopping PPM signals in (1) to convey information, the difference being the TH code used for each user. Also, all the users experience the same multipath environment, although each one has its own multipath trajectory. When  $N_u$  asynchronous transmitters are active, the received signal at user one's receiver position is modeled as

$$r(t) = \sum_{\nu=1}^{N_u} A^{(\nu)} \Psi^{(\nu)}(\xi^{(\nu)}, t - \tau^{(\nu)}) + n(t), \quad (9)$$

where  $\tau^{(\nu)}$  represent time asynchronisms between the clock of user  $\nu$ 's transmitter and user one's receiver,  $(A^{(\nu)})^2$  is the ratio of average power used by user  $\nu$ 's transmitter with respect to the average power used by user one's transmitter (with  $(A^{(1)})^2 = 1$ ), and  $n(t)$  represents non MUI interference modeled as AWGN.

The signal  $r(t)$  in (9) is a random process that depends on the random noise  $n(t)$  and three other types of random variables: The random time delays, denoted by the vector  $\underline{\tau} = (\tau^{(2)}, \tau^{(3)}, \dots, \tau^{(N_u)})$ ; the random time hopping codes, denoted by the vector  $\underline{C} = (C^{(2)}, C^{(3)}, \dots, C^{(N_u)})$ , where each code  $C^{(\nu)} = \{c_k^{(\nu)}\}$  for  $k = 0, 1, \dots, N_s - 1$ ; and the random multiple-path trajectories indexes, denoted by  $\xi^{(1)}$  and the vector  $\underline{\xi} = (\xi^{(2)}, \xi^{(3)}, \dots, \xi^{(N_u)})$ . Performance computation is based on signal-to-interference (SIR) ratios and BER rates averaged over all random variables.

To facilitate our analytical treatment, the following assumptions are made

1. We can treat  $\xi^{(\nu)}$ ,  $\nu = 1, 2, \dots, N_u$ , as independent, identically distributed (i.i.d.) random variables, with each  $\xi^{(\nu)}$  uniformly distributed over its range. The expected values with respect to  $\xi^{(\nu)}$  can be approximated with sample averages based on parameters calculated using measured or synthesized received waveforms as in [15]. The  $\int_{-\infty}^{\infty} p(\xi^{(\nu)}, t) dt \simeq 0$ .
2. The receiver is able to perfectly match user one's received signal, and it will be assumed to be perfectly synchronized.
3. Since  $\delta \ll T_f$  we will assume  $\delta = 0$  for  $\nu = 2, 3, \dots, N_u$ .
4. The elements of the TH code are i.i.d random variables. Each  $c_k^{(\nu)}$  is uniformly distributed on the interval  $[0, N_h]$ . We don't specify  $N_h$  because the assumption 6) produce results independent of it.
5. The transmission time differences  $\tau^{(\nu)} - \tau^{(1)} \triangleq \Phi^{(\nu)} T_f + \phi^{(\nu)}$ , for  $\nu = 2, \dots, N_u$ , are i.i.d random variables, with  $\phi^{(\nu)} \triangleq \tau^{(\nu)} - \tau^{(1)} \bmod T_f$  being uniformly distributed on  $[0, T_f]$ , where mod means the modulus operation. We don't characterize  $\Phi^{(\nu)}$  because results will be independent of it.
6. To avoid overlapping of pulses belonging to different frames in (1) the maximum time shift produced by the TH code is limited to  $N_h T_c < ((T_f - T_a)/2) - \epsilon$ , where  $\epsilon \triangleq 2(T_p + \delta)$ . Combining this condition, together with

$T_f > (T_a + \delta)$ , we can ensure that both inter-pulse and inter-symbol interference can be neglected.

With these assumptions the net effect of the multiple access interference at the output of the demodulation circuit can be modeled as a zero mean Gaussian random variable (r.v.).<sup>3</sup>

### 3 Receiver Signal Processing and Performance

To simplify notation, in the following analysis we will drop the super-index <sup>(1)</sup> from  $\Psi^{(1)}(\xi^{(1)}, t)$ ,  $A^{(1)}$ ,  $\tau^{(1)}$ , and  $c^{(1)}$ .

#### 3.1 Signal Detection

Let's assume that the receiver wants to demodulate user one's signal. The received signal  $r(t)$  in (9) can be rewritten

$$r(t) = A\Psi(\xi, t - \tau) + n_{\text{TOT}}(t), \quad t \in \mathcal{T}, \quad (10)$$

where  $\mathcal{T} \triangleq [\tau, N_s T_f + \tau]$ , and

$$n_{\text{TOT}}(t) \triangleq \sum_{\nu=2}^{N_u} A^{(\nu)}\Psi^{(\nu)}(\xi^{(\nu)}, t - \tau^{(\nu)}) + n(t).$$

For the time being, let's assume that user one's receiver is static at one place, and that user one's transmitter is at a fixed position, i.e.,  $\xi$  is kept fixed.

In the present analysis signal detection is achieved using a Rake receiver [17]. For binary communications a perfectly synchronized rake Receiver will have 2 filters matched to  $\Psi_j(\xi, t - \tau)$ ,  $j = 1, 2$ . The output of the  $j^{\text{th}}$  matched filter

$$y_j = \int_{t \in \mathcal{T}} r(t) \Psi_j(\xi, t - \tau) dt \triangleq y_s + y_m + y_n, \quad (11)$$

can be seen as the sum of three outputs: the output  $y_s$  of a filter perfectly matched and synchronized to the signal, the output  $y_m$  of a filter mismatched and asynchronous to the interference, and the output  $y_n$  consisting of filtered noise.

The signal term  $y_s$  takes into account the correlation of the desired user with itself

$$y_s = \int_{t \in \mathcal{T}} A \Psi(\xi, t - \tau) \Psi_j(\xi, t - \tau) dt = \begin{cases} E_{\Psi}(\xi), & \text{for } \Psi(\cdot) = \Psi_j(\cdot), \\ E_{\Psi}(\xi) \beta(\xi), & \text{for } \Psi(\cdot) \neq \Psi_j(\cdot), \end{cases} \quad (12)$$

<sup>3</sup> For the case under study, i.e., signals with several pulses per bit  $N_s$ , the Gaussian approximation for the effect of the MUI at the output of the correlator is justified by the central limit theorem for various users  $N_u$ , and has been used repeatedly by several authors. In particular, the results in [16] shows that for the values of  $N_s$  and  $N_u$  considered here the MUI effects can be modeled as produced by a Gaussian r.v..

The multiple-access term  $y_m$  takes into account the cross-correlation among user one and the interfering users

$$\begin{aligned} y_m &= \int_{t \in \mathcal{T}} \sum_{\nu=2}^{N_u} A^{(\nu)} \Psi^{(\nu)}(\xi^{(\nu)}, t - \tau^{(\nu)}) \Psi_j(\xi, t - \tau) dt \\ &= \sum_{\nu=2}^{N_u} \sum_{k=0}^{N_s-1} A^{(\nu)} E_a \tilde{\alpha}^2(\xi, \xi^{(\nu)}, \tau^{(\nu)}) \tilde{\gamma}(\xi, \xi^{(\nu)}, \Omega_k^{(\nu)} - \phi^{(\nu)} - (b_{j_1} - b_j)\delta) \end{aligned} \quad (13)$$

where  $\Omega_k^{(\nu)} \triangleq c_{k-\phi^{(\nu)}}^{(\nu)} - c_k$ .

Finally, the noise term is

$$y_n = \int_{t \in \mathcal{T}} n(t) \Psi_j(\xi, t - \tau) dt. \quad (14)$$

### 3.2 Performance Conditioned on $\xi$

The performance of such correlation receiver can be analyzed using traditional detection theory [18],<sup>4</sup> and the demodulation problem can be analyzed as the time-shift-coherent detection of  $M$  equal-energy, equally-likely signals in the presence of Gaussian interference plus noise using a binary correlation receiver. The resulting performance results should be considered as a lower bound, i.e., performance of an ideal Rake receiver.

The BER is given by

$$\text{UBPe}(N_u|\xi) = \frac{M}{2} \int_{\sqrt{\text{SIR}_{\text{out}}(N_u|\xi)}}^{\infty} \frac{\exp(-\rho^2/2)}{\sqrt{2\pi}} d\rho, \quad (15)$$

where

$$\text{SIR}_{\text{out}}(N_u|\xi) \triangleq \frac{1}{[\text{SIR}_{\text{out}}(1|\xi)]^{-1} + [\text{SIR}_{\text{MUI}}(N_u|\xi)]^{-1}}, \quad (16)$$

is the output bit SIR observed in the presence of  $N_u - 1$  other users and, for the time being, is being conditioned on  $\xi$ . The

$$\text{SIR}_{\text{out}}(1|\xi) \triangleq \frac{E_s \alpha^2(\xi) [1 - \beta(\xi)]}{N_o} \quad (17)$$

is the bit SNR in the presence of AWGN and in the absence of MUI, and

$$\text{SIR}_{\text{MUI}}(N_u|\xi) \triangleq \frac{E_s \alpha^2(\xi) [1 - \beta(\xi)]}{N_{\text{MUI}}(\xi)} \simeq \frac{\mathcal{G}(\xi)}{N_u}, \quad (18)$$

is the bit SNR in the presence of MUI and in the absence of AWGN, where  $N_{\text{MUI}}(\xi)$  is the *equivalent* PSD level of the total MUI, and where  $\mathcal{G}(\xi) \triangleq \frac{\mu(\xi)}{T_i \mathcal{R}_l}$  is

<sup>4</sup> Since the MUI is modeled as Gaussian noise, this correlation receiver is sub-optimum, the optimum receiver being a multi-user detector [19].

a *random* processing gain factor, where  $R_b = 1/T_s$  is the bit transmission rate, and where

$$\mu(\xi) = \frac{m_p^2(\xi, \xi, 0, 0, \delta)}{\mathbf{E}_{(\xi^{(\nu)}|\xi)}\{\int_{-\infty}^{\infty} m_p^2(\xi, \xi^{(\nu)}, \varsigma, 0, \delta) d\varsigma\}} \quad (19)$$

is a normalized random SIR parameter defined in terms of both the received UWB pulse shape and the time-shift defining the orthogonal PPM data modulation, where  $\mathbf{E}_{(\xi^{(\nu)}|\xi)}\{\cdot\}$  is the expected value with respect to  $\xi^{(\nu)}$  conditioned on  $\xi$ , and where

$$\begin{aligned} m_p(\xi, \xi^{(\nu)}, \varsigma, 0, \delta) &\triangleq \int_{-\infty}^{\infty} p(\xi^{(\nu)}, \varrho) [p(\xi, \varrho) - p(\xi, \varrho - \delta)] d\varrho \\ &= \begin{cases} \alpha^2(\xi) \times \\ [\gamma(\xi, \varsigma) - \gamma(\xi, \varsigma - \delta)], & \text{for } \nu = 1, \\ \tilde{\alpha}^2(\xi, \xi^{(\nu)}) \times \\ [\tilde{\gamma}(\xi, \xi^{(\nu)}, \varsigma) - \tilde{\gamma}(\xi, \xi^{(\nu)}, \varsigma - \delta)] & , \text{for } \nu \neq 1, \end{cases} \quad (20) \end{aligned}$$

The averaged performance can be obtained by taking the expected value  $\mathbf{E}_{\xi}\{\cdot\}$  of (15) over all values of  $\xi$  to get

$$\overline{\text{UBPe}}\left(\frac{\bar{E}_s}{N_o}, N_u\right) = \mathbf{E}_{\xi}\{\text{UBPe}(N_u|\xi)\}. \quad (21)$$

## 4 Numerical Results

### 4.1 UWB Pulse

In this numerical example the UWB pulse is the second derivative of a Gaussian pulse

$$p(t) = \left[1 - 4\pi \left[\frac{t}{t_n}\right]^2\right] \exp\left(-2\pi \left[\frac{t}{t_n}\right]^2\right), \quad (22)$$

for  $-T_p/2 \leq t \leq T_p/2$ , where  $t_n$  is a parameter that determine the pulse duration. The pulse energy  $E_p = 3t_n/8$ . For this pulse the signal correlation function is

$$\gamma(\tau) = \left[1 - 4\pi \left[\frac{\tau}{t_n}\right]^2 + \frac{4\pi^2}{3} \left[\frac{\tau}{t_n}\right]^4\right] \exp\left(-\pi \left[\frac{\tau}{t_n}\right]^2\right), \quad (23)$$

for  $-T_p \leq \tau \leq T_p$ .

For  $t_n = 0.7531$  ns we get a pulse duration  $T_p \simeq 2.0$  ns. In this case the spectrum of  $p(t)$  is centered at about 1.1 GHz, with a 3 dB bandwidth of about 1.2 GHz, easily satisfying the traditional definition of UWB signal stating that the 10 dB bandwidth of the signal should be at least 20 percent of its center frequency [14]. Fig. 1 shows this pulse.

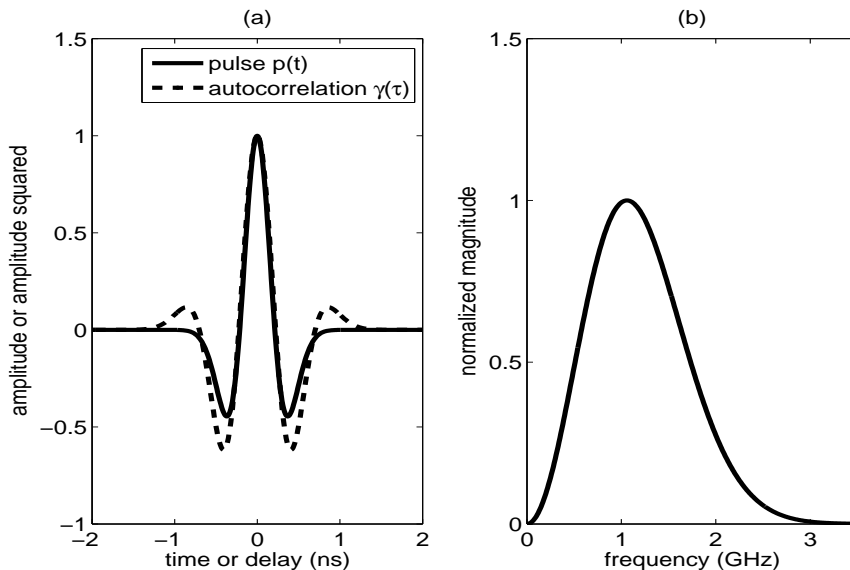


Fig. 1. The plots for (a)  $p(t)$ , (b)  $\gamma(\tau)$ , and (c) the spectrum of  $p(t)$

The set of  $p(\xi^{(\nu)}, t)$  were taken from the Time Domain Corporation Indoor Channel Database, available at USC's ULTRA-LAB WEB site at [http://click.usc.edu/New\\_Site/database.html](http://click.usc.edu/New_Site/database.html). These UWB "pulses" have an average delay spread  $T_a \simeq 300$  ns.

## 4.2 Calculations

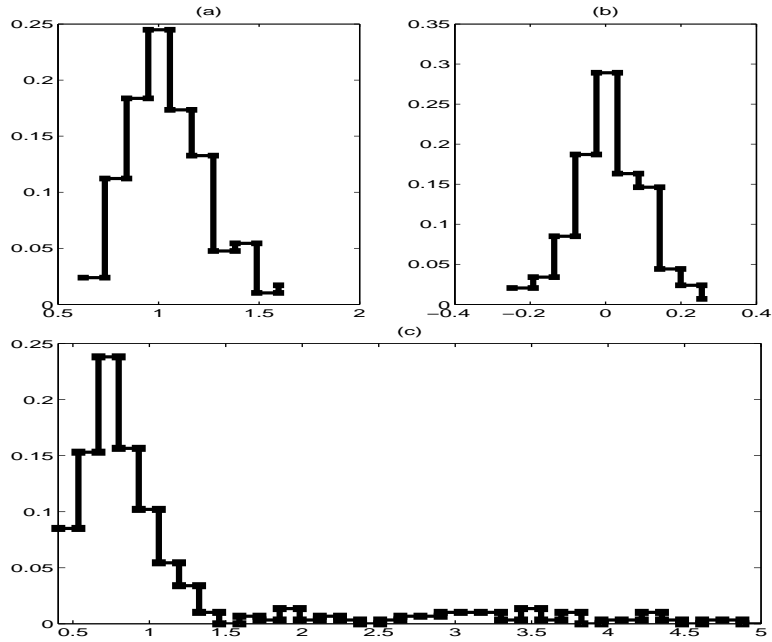
For this example we use  $T_f = 350$  ns and  $R_b = 100$  to  $R_b = 1000$  kilobits per second (Kbps) per user. For the Gaussian case we use  $\alpha^2 = 1$  and  $\beta = 0$  and calculate  $\mu \simeq 1.3$ . For the multipath case fig. 2 depicts histograms for  $\alpha^2(\xi)$ ,  $\beta(\xi)$  and  $\mu(\xi)$ .

Fig. 3(a) shows BER vs.  $Nu$  for  $R_b = 100, 500, 1000$  kbps. Fig. 3(b) shows the number of users  $Nu$  to preserve a BER value for  $R_b = 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000$  Kbps.<sup>5</sup>

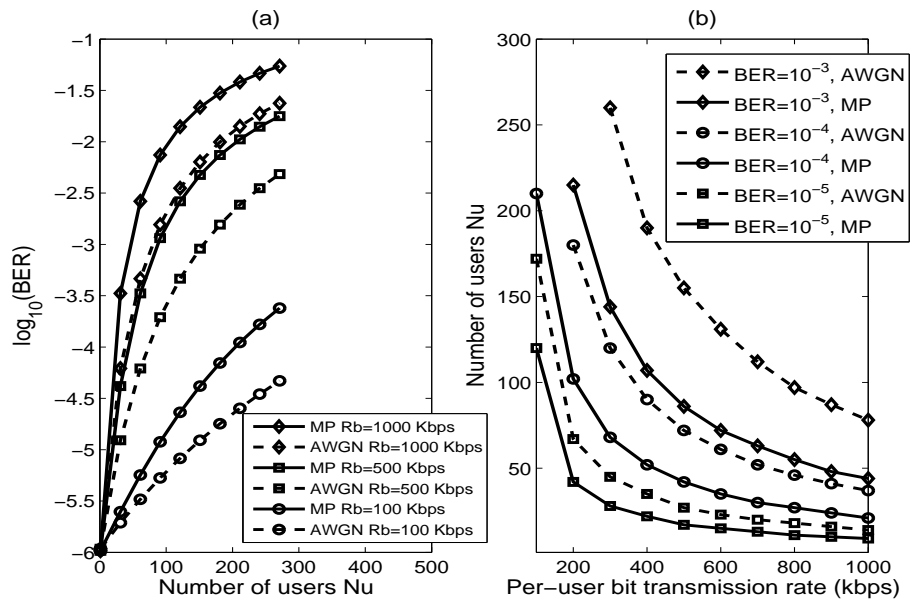
## 5 Conclusions.

In this work we study UWB SSMA based on PPM-TH. We analyze the effects of the transmission rate in the number of users for different BER.

<sup>5</sup> Similar to [15], the calculations for the multipath case are based on sample averages over the different realizations of  $\alpha^2(\xi)$ ,  $\beta(\xi)$  and  $\mu(\xi)$  considering a sample size of 49 for every room, and averaging the results over 5 rooms.



**Fig. 2.** The histograms for (a)  $\alpha^2(\xi)$ , (b)  $\beta(\xi)$ , and (c)  $\mu(\xi)$ . The ordinate represents appearance frequency, and the abscissa represents the value of the parameter.



**Fig. 3.** (a)  $BER$  vs. number of users for different  $R_b$ . (b) Number of users to preserve  $BER$  for a given  $R_b$

Fig. 3(b) shows the number of users  $N_u$  to preserve a BER value for different values of  $R_b$  in Kbps. For the BER and SIR values in Fig. 3(a),  $\text{SIR}_{\text{MUT}}(N_u|\xi)$  dominates over  $\text{SIR}_{\text{out}}(1|\xi)$  and therefore  $N_u \simeq \frac{1}{\text{SIR}_{\text{out}}(N_u|\xi)} \frac{\mu(\xi)/T_f}{R_b}$ .

For the type of signals and indoor office channel under consideration, these result indicate the following:

- For BER= $10^{-5}$ , e.g., in data applications requiring low BER, the number of simultaneous radio links decreases from more than 100 to less than 10 when  $R_b$  goes from 100 kbps to 1000 kbps. This corresponds to a decrease in a factor in the order of 10 in the processing gain.
- For BER= $10^{-3}$ , e.g., in voice applications requiring low BER, the number of simultaneous radio links decreases from more than 200 to less than 50 when  $R_b$  goes from 300 kbps to 1000 kbps. This corresponds to a decrease in a factor in the order of 3.4 in the processing gain.
- To obtain a combination with  $N_u \geq 100$  users,  $R_b \geq 1$  Megabits per second, and BER  $\leq 10^{-5}$ , some form of forward error correction must be used.

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