An Investigation of Antenna and Multipath Effects on Pulse-Based UWB Using FSK

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***Abstract*— In this work, we study ultra wideband (UWB) communications over dense multipath channels using frequency shift keying (FSK) data modulation. We take into account the effects of both the antenna system and the multipath channel, and calculate the signal-to-noise ratio (SNR) degradation for different frequency deviations.**

I. Introduction

Ultra wideband communications for short-range high-speed wireless communications has been studied extensively [1]-[5]. Several authors have studied the performance of different modulation techniques under different channel conditions with different receiver architectures.

Early work studied communications using *M-ary* pulse position modulation (PPM) with ideal Rake receiver [6] and with lower complexity Rake receivers [7]. Other modulation schemes and channel models have also been studied. In [8] communications using PPM and on-off-keying modulation with ideal and sub-optimum Rake receivers is studied. In [9] communications using binary PPM comparing ideal Rake receiver versus reduced complexity Rake receivers using a statistical multipath channel model from an office building is analyzed. In [10] communications with an orthogonal frequency division multiplexing (OFDM) system using QPSK modulation with a multipath channel for residential environments is presented. In [11] performance evaluation of direct sequence DS-UWB within a home environment is studied. In [12] performance analysis using orthogonal PPM UWB over a multipath channel also for residential environments is presented.

Recent work has proposed the use of frequency modulation for UWB communications.[1] In [13] an UWB modulation scheme that combines properties of both frequency shift keying and pulse position modulation using pulses from different frequency band is studied. In [14] authors present a wideband FM technique to generate a constant-envelope UWB signal where Data is modulated on a sub-carrier using FSK techniques. In [15] a method for high data rate transmission through the exploitation of the orthogonality of the modified Hermite polynomial function is presented. In [16] performance in additive white Gaussian noise (AWGN) of a form of M-ary FSK using orthonormal pulses derived from a parametric closed-form solution is studied.

This work studies the performance of binary FSK UWB communications using and ideal Rake receiver in the presence of AWGN and dense multipath effects (DME). We use an autoregressive (AR) channel model to represent the small scale fading introduced by the multipath environment. We also include the effects of large scale fading with a lognormal shadow fading model for the path loss (PL). This channel model was first proposed in [17] [18] and modified in [12].

We take into account the effects of both the antenna system and the multipath channel, and calculate the SNR degradation for different frequency deviations.

The organization of this paper is as follows. In Section II we introduce the transmitter, and the models of the Gaussian and multipath channels. In Section III we describe the signal processing at the receiver. Section IV contains the numerical results.

II. System Model

A. Transmitted Signals

The *transmitted* FSK signal is described by

$$\Psi_{\text{TX}}(t) = \sum_{k=0}^{N_p-1} p_{\text{TX}}(t - kT_f, d\,\Delta, \psi)\ , \qquad (1)$$

where $p_{\text{TX}}(t, \Delta, \psi)$ is the basic pulse with duration T_p and phase ψ, k indexes the number of pulses that has been transmitted, T_f is the frame time between pulse transmissions with $T_f >> T_p$, ψ is the phase of the oscillator used to produce $\Psi_{\text{TX}}(t)$, and d is the data bit that takes one of two equally likely values from the binary set $\{-1, +1\}$. For a given frequency shift parameter Δ, the data bit d provides a frequency shift to the N_p pulses in the bit waveform $\Psi_{\text{TX}}(t)$. The duration of the bit waveform is $T_b = N_p T_f$.

This pulse $p_{\text{TX}}(t, \Delta, \psi)$ is the UWB signal. 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 its fractional bandwidth

[1] Given the huge bandwidth available for UWB, M-ary orthogonal signaling based on frequency modulation is an alternative for exchanging bandwidth for power.

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(the ratio of the 10 dB bandwidth to the central frequency) is at least 20 percent [19].

The noise $n(t)$ at the receiver's input is additive white Gaussian noise (AWGN) with two-sided power spectrum density (PSD) $(N_o/2)$.

B. Gaussian Channel Model

If the channel is Gaussian in general the received signal is modified by amplitude A_o and delay τ_o factors that depend on the transmitter-receiver separation distance (we assume that both $A_o = 0$ and $\tau_o = 0$).

We also assume that, for the range of frequencies of interest, the effect of the antenna system can be modeled as a derivative operation, or alternatively

$$p_{\text{TX}}(t, \Delta, \psi) = \int_{-\infty}^{t} p(\varrho, \Delta, \psi)\, d\varrho \ , \tag{2}$$

where $p_{\text{TX}}(t, \Delta, \psi)$ and $p(t, \Delta, \psi)$ are the transmitted and received pulses, respectively. This model for the antenna system has been repeatedly used, however, most existing UWB antennas do not have the differentiation effect [1]- [5]. Even for those antennas systems, the methodology of analysis in this work still can be applied because it is based on the energy and correlation values of the *received* signals.

1) Channel Effect on the UWB Pulse: For simplicity of analysis, we consider pulses $p(t, \Delta, \psi)$ based on windowed sinewaves with carrier frequency $f_c = (Q/T_o)$ and spectrum given by

$$\begin{aligned} &F_p(f, \Delta, \psi) \\ &= \ w(f)\left[-j\pi T_o \exp\left(-j\pi T_o f\right) \exp\left(j\frac{f}{f_c+\Delta}\psi\right) \times \right. \\ &\quad \left.\left(\frac{f_c+\Delta}{f_c}\right) \operatorname{sinc}(\pi T_o(f-(f_c+\Delta)))\ \right] , \end{aligned} \tag{3}$$

for $f \geq 0$, where $\operatorname{sinc}(\cdot) = \sin(\cdot)/(\cdot)$, Q is a positive integer, T_o is the duration of the pulse when the rectangular window $w(f) = 1$ for all f is used, and T_p is the duration of the pulse when $w(f)$ is a Kaiser window. The Kaiser window is centered at f_c and has the same bandwidth as the channel model used to generate the received pulse.

For $Q = 15$ and $T_o = 3.0$ ns the pulse $p(t, 0, 0)$, shown on Fig. 1, has duration $T_p \simeq 4$ ns and the spectrum $F_p(f, 0, 0)$ is centered at $f_c = 5$ GHz, with a 10 dB bandwidth of about 480 MHz, approximately satisfying the definition of UWB signal. Although this pulse does not strictly satisfy the FCC definition, the FSK signals after modulation do.

The pulse energy is

$$\begin{aligned} E_p(\Delta) \ &\triangleq \ \int_{-\infty}^{\infty} |p(t, \Delta, \psi|^2\, dt \ = \ \int_{-\infty}^{\infty} |F_p(f, \Delta, \psi)|^2\, df \\ &\simeq \ \left(\frac{f_c+\Delta}{f_c}\right)^2 \int_{-\infty}^{\infty} |F_p(f, 0, 0)|^2\, df \\ &\triangleq \ \left(\frac{f_c+\Delta}{f_c}\right)^2 E_p(0) \ , \end{aligned} \tag{4}$$

and the normalized pulse correlation function is

$$\begin{aligned} \gamma(\Delta_1 - \Delta_2) \ &\overset{(i)}{\simeq} \ \gamma(\Delta_1, \Delta 2, \psi, \psi) \\ &\triangleq \ \frac{\int_{-\infty}^{\infty} p(t, \Delta_1, \psi)\, p(t, \Delta_2, \psi)\, dt}{\sqrt{E_p(\Delta_1) E_p(\Delta_2)}} \\ &= \ \frac{\int_{-\infty}^{\infty} \ F_p(f, \Delta_1, \psi)\, F_p^*(f, \Delta_2, \psi)\, df}{\sqrt{E_p(\Delta_1) E_p(\Delta_2)}} \ , \end{aligned} \tag{5}$$

where Δ_1 and $\Delta 2$ are the frequency shifts used to distinguish the binary signals, and where approximation (i) holds since $(2f_c + \Delta_1 + \Delta_2) >> 1/T_p$. From Fig. 1 we see that $\gamma(\Delta)$ has the first zero-crossings at $\Delta = \Delta_1 - \Delta_2 \simeq 0.3715$ GHz, it has the second zero-crossings at $\Delta = \Delta_1 - \Delta_2 \simeq 0.7415$ GHz, and has a minimum value $\gamma(0.5375 \cdot 10^9) \simeq -0.2443$.

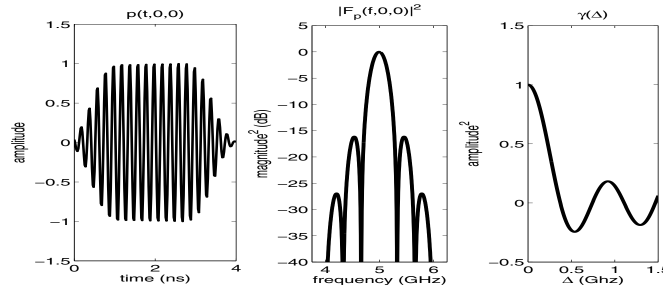

Fig. 1. The normalized plots for $p(t, 0, 0)$, $|F_p(f, 0, 0)|^2$, and $\gamma(\Delta)$.

C. FSK Signals in Gaussian Channels

Under free-space propagation conditions the received FSK signal is denoted

$$\Psi_i(t) = \sum_{k=0}^{N_p-1} p(t - kT_f, d_i\, \Delta, \psi), \tag{6}$$

for $i = 1, 2$. The signals $\Psi_i(t)$ in (6) have duration $T_b = N_p T_f$ and energy

$$E_{\Psi_i} \ \triangleq \ \int_{-\infty}^{\infty} [\Psi_i(t)]^2 dt \ = \ N_p \left(1 + \frac{d_i\, \Delta}{f_c}\right)^2 E_p(0) \ . \tag{7}$$

The signals $\Psi(t)$ have normalized correlation values

$$\begin{aligned} \beta_{ij} \ &\triangleq \ \frac{\int_{-\infty}^{\infty} \Psi_i(t)\, \Psi_j(t)\, dt}{\sqrt{E_{\Psi_i} E_{\Psi_j}}} \\ &\simeq \ \begin{cases} 1\,, & i = j\ , \\ \gamma(2\,\Delta)\ , & i \neq j\ . \end{cases} \end{aligned} \tag{8}$$

The frequency shift value $\Delta = \Delta_o \simeq 0.3715/2 \simeq 0.1858$ GHz[2] is chosen to get binary orthogonal signals in the absence of multipath, i.e., $\beta_{ij} = 0$, $i \neq j$.

[2]The feasibility of an oscillator capable of such a high frequency deviation may need to be investigated.

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D. Multipath Channel Model

We consider a slowly time varying indoor channel. The link between the transmitter and the receiver defines a random path (or trajectory) that is a function of the relative position of the receiver with respect to the position of the transmitter. The random trajectory will be identified with the index ξ.

Assume that the transmitter stays fixed. As we move the receiver in a spatially random fashion, the trajectory changes and the received waveform also changes. Since the channel is slowly time varying, the channel properties (i.e., the random trajectory) remain constant over N_p pulses.

1) Channel Effect on the UWB Pulse: In an indoor multipath channel, transmission of the pulse $p_{\text{TX}}(t,\Delta,\psi)$ results in the reception of a random "pulse" $\sqrt{E_a}\,p(\xi,t,\Delta,\psi)$ which is a multipath spread version of $p(t,\Delta,\psi)$, and that has a spectrum given by

$$\sqrt{E_a}\,F_p(\xi,f,\Delta,\psi) \;=\; F_p(f,\Delta,\psi)\,H(\xi,f), \tag{9}$$

where $H(\xi,f)$ is spectrum of the multipath channel, which is of random nature. Since the receiver moves slowly it can be assumed that the frequency shift Δ is not modified by the channel.

The average duration of $p(\xi,t,\Delta,\psi)$ is denoted T_a, and can have a value up to a few hundreds of nanoseconds, hence $T_a >> T_p$. We will assume that T_a is equal to the mean delay spread of the channel.

The pulse $\sqrt{E_a}\,p(\xi,t,\Delta,\psi)$ has energy that is random:

$$E_p(\xi,\Delta) \triangleq E_a\,\alpha^2(\xi,\Delta)\;, \tag{10}$$

where E_a is the average received energy, and

$$\begin{aligned}\alpha^2(\xi,\Delta) &\triangleq \int_{-\infty}^{\infty}[p(\xi,t,\Delta,\psi)]^2dt \\ &\simeq \left(\frac{f_c+\Delta}{f_c}\right)^2\int_{-\infty}^{\infty}|\tilde{F}_p(\xi,f,\Delta,\psi)|^2\,df \\ &\triangleq \left(\frac{f_c+\Delta}{f_c}\right)^2\tilde{\alpha}^2(\xi,\Delta)\;,\end{aligned} \tag{11}$$

is the normalized random energy, where

$$F_p(\xi,f,\Delta,\psi) \;\triangleq\; \left(\frac{f_c+\Delta}{f_c}\right)\tilde{F}_p(\xi,f,\Delta,\psi). \tag{12}$$

The pulse has normalized random signal correlation

$$\begin{aligned}&\gamma(\xi,\Delta_1-\Delta_2) \\ &\overset{(ii)}{\simeq} \;\gamma(\xi,\Delta_1,\Delta_2,\psi,\psi) \\ &\triangleq \;\frac{\int_{-\infty}^{\infty}p(\xi,t,\Delta_1,\psi)\,p(\xi,t,\Delta_2,\psi)\,dt}{\sqrt{\alpha^2(\xi,\Delta_1)\,\alpha^2(\xi,\Delta_2)}} \\ &= \;\int_{-\infty}^{\infty}\frac{F_p(\xi,f,\Delta_1,\psi)\,F_p^*(f,\Delta_2,\psi)\,df}{\sqrt{\alpha^2(\xi,\Delta_1)\,\alpha^2(\xi,\Delta_2)}}\;,\end{aligned} \tag{13}$$

where the approximation in (ii) assumes that the random function $\gamma(\xi,\Delta_1,\Delta_2,\psi,\psi)$ can be seen as having a mean $\gamma(\Delta_1-\Delta_2)$ which is a function of $\Delta_1-\Delta_2$ but independent of ξ, plus a random component depending on Δ_1,Δ_2,ψ and ξ.

The set of received UWB pulses $p(\xi,t,\Delta,\psi)$ is generated using an autoregressive channel model [17] [18] to form and ensemble of channel pulse responses. These UWB "pulses" have an average delay spread $T_a \simeq 160$ ns. Fig. 2 shows one realization of this pulse.

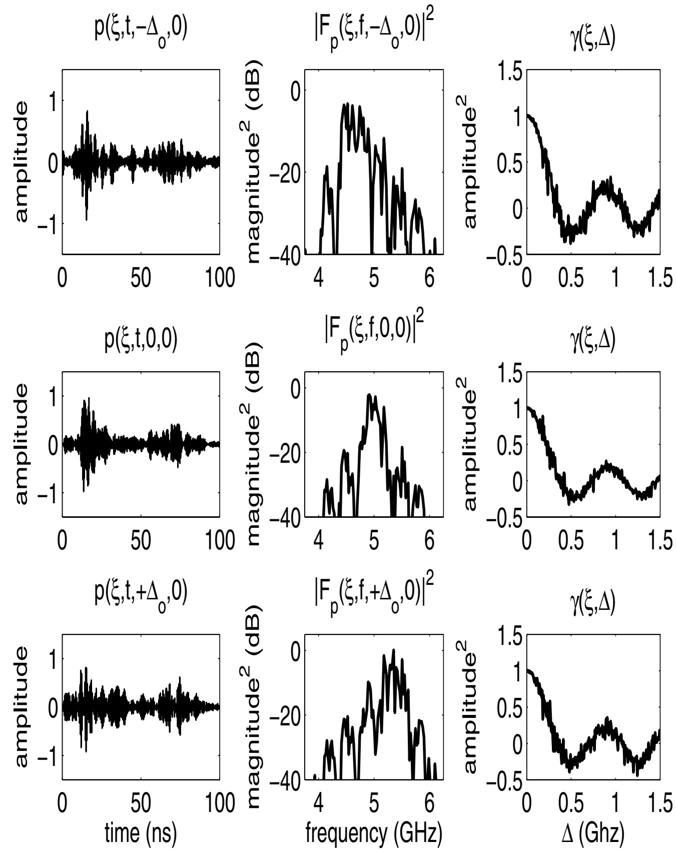

Fig. 2. The normalized plots for: (top) $p(\xi,t,-\Delta_o,0)$, $|F_p(\xi,f,-\Delta_o,0)|^2$, and $\gamma(\xi,\Delta)$, (middle) $p(\xi,t,0,0)$, $|F_p(\xi,f,0,0)|^2$, and $\gamma(\xi,\Delta)$, and finally (bottom) $p(\xi,t,+\Delta_o,0)$, $|F_p(\xi,f,+\Delta_o,0)|^2$, and $\gamma(\xi,\Delta)$, where $\Delta_o \simeq 0.3715/2 \simeq 0.1858$ GHz.

E. FSK Signals in Multipath

The signals received in the presence of multipath are

$$\Psi_i(\xi,t) = \sum_{k=0}^{N_p-1} p(\xi,t-kT_f,d_i\,\Delta,\psi). \tag{14}$$

The signal in (14) is received with trajectory ξ, and is a multipath spread version of the signal in (6). We will assume that $\Psi(\xi,t)$ has fixed duration $T_b \simeq N_pT_f$ with $T_f \geq T_a$.

The signals $\Psi_i(\xi,t)$ have random energy

$$E_{\Psi_i}(\xi) \triangleq \int_{-\infty}^{\infty} [\Psi_i(\xi,t)]^2 dt = \sum_{k=0}^{N_p-1} E_p(\xi, d_i\,\Delta) \simeq N_p \left(1+\frac{d_i\,\Delta}{f_c}\right)^2 E_a\,\tilde{\alpha}^2(\xi, d_i\,\Delta)\,. \quad (15)$$

The signals $\Psi(t)$ have normalized random correlation values

$$\beta_{ij}(\xi) \triangleq \frac{\int_{-\infty}^{\infty} \Psi_i(\xi,t)\,\Psi_j(\xi,t)\,dt}{\sqrt{E_{\Psi_i}(\xi)\,E_{\Psi_j}(\xi)}} \simeq \begin{cases} 1\,, & i=j\,,\\ \gamma(\xi, 2\,\Delta)\,, & i\neq j\,. \end{cases} \quad (16)$$

From fig. 2 we observe that the frequency shift value $\Delta_o \simeq 0.1858$ GHz results in $\beta_{ij}(\xi)\neq 0$, $i\neq j$.

III. Receiver Signal Processing and Performance

For the time being, let's assume that both the receiver and the receiver are at fixed locations, i.e., ξ is kept fixed. Hence, bit error rate (BER) results will be conditioned on ξ.

The received signal can be written as

$$r(t) = \Psi_i(\xi,t) + n(t), \quad i=1,2\,. \quad (17)$$

In the present analysis signal detection is achieved using a Rake receiver [21], and the demodulation problem can be analyzed as the coherent detection of 2 *quasi*-orthogonal, unequal-energy, equally-likely signals in the presence of AWGN. For binary communications a perfectly synchronized Rake Receiver will have 2 filters matched to $\Psi_i(\xi, t-\tau)$, $i=1,2$.

The performance of such correlation receiver can be analyzed using traditional detection theory [22]. The performance results should be considered as a lower bound, i.e., performance of an ideal Rake receiver. The bit error rate (BER) of this receiver is given by

$$\text{BER}(\xi) = \frac{Q\left(\frac{m_2(\xi)-T(\xi)}{\sigma_y(\xi)}\right)}{2} + \frac{Q\left(\frac{T(\xi)-m_1(\xi)}{\sigma_y(\xi)}\right)}{2}\,, \quad (18)$$

where $Q(\cdot)$ is the Gaussian-tail integral, $T(\xi) = (E_{\Psi_2}(\xi) - E_{\Psi_1}(\xi))/2$ is a decision threshold,

$$\begin{aligned} m_i(\xi) &= \int_0^{T_b} \Psi_i(\xi,t)\,[\Psi_2(\xi,t)-\Psi_1(\xi,t)]\,dt,\\ m_1(\xi) &= -E_{\Psi_1}(\xi)\,[1-\sqrt{E_{\Psi_2}(\xi)/E_{\Psi_1}(\xi)}\,\beta_{12}(\xi)],\\ m_2(\xi) &= +E_{\Psi_2}(\xi)\,[1-\sqrt{E_{\Psi_1}(\xi)/E_{\Psi_2}(\xi)}\,\beta_{21}(\xi)], \end{aligned} \quad (19)$$

and

$$\begin{aligned} \sigma_y^2(\xi) &= \left(\frac{N_o}{2}\right)\int_0^{T_b} [\Psi_2(\xi,t)-\Psi_1(\xi,t)]^2\,dt\\ &= \left(\frac{N_o}{2}\right) \times [E_{\Psi_1}(\xi)+E_{\Psi_2}(\xi) - 2\sqrt{E_{\Psi_1}(\xi)\,E_{\Psi_2}(\xi)}\,\beta_{12}(\xi)]\,, \end{aligned} \quad (20)$$

therefore

$$\left(\frac{m_1(\xi)}{\sigma_y(\xi)}\right) = -\sqrt{\frac{E_{\Psi_1}(\xi)}{N_o}} \times \sqrt{\frac{[1-\frac{(f_c+\Delta)}{(f_c-\Delta)}\frac{\tilde{\alpha}(\xi,+\Delta)}{\tilde{\alpha}(\xi,-\Delta)}\,\gamma(\xi,2\,\Delta)]^2}{[\frac{1}{2}+\frac{1}{2}\frac{(f_c+\Delta)^2}{(f_c-\Delta)^2}\frac{\tilde{\alpha}^2(\xi,+\Delta)}{\tilde{\alpha}^2(\xi,-\Delta)} - \frac{(f_c+\Delta)}{(f_c-\Delta)}\frac{\tilde{\alpha}(\xi,+\Delta)}{\tilde{\alpha}(\xi,-\Delta)}\,\gamma(\xi,2\,\Delta)]}} \quad (21)$$

and

$$\left(\frac{m_2(\xi)}{\sigma_y(\xi)}\right) = +\sqrt{\frac{E_{\Psi_2}(\xi)}{N_o}} \times \sqrt{\frac{[1-\frac{(f_c-\Delta)}{(f_c+\Delta)}\frac{\tilde{\alpha}(\xi,-\Delta)}{\tilde{\alpha}(\xi,+\Delta)}\,\gamma(\xi,2\,\Delta)]^2}{[\frac{1}{2}+\frac{1}{2}\frac{(f_c-\Delta)^2}{(f_c+\Delta)^2}\frac{\tilde{\alpha}^2(\xi,-\Delta)}{\tilde{\alpha}^2(\xi,+\Delta)} - \frac{(f_c-\Delta)}{(f_c+\Delta)}\frac{\tilde{\alpha}(\xi,-\Delta)}{\tilde{\alpha}(\xi,+\Delta)}\,\gamma(\xi,2\,\Delta)]}} \quad (22)$$

The averaged performance can be obtained by taking the expected value $\mathbf{E}_\xi\{\cdot\}$ of (18) over all values of ξ to get

$$\overline{\text{BER}}\left(\frac{\overline{E}_b}{N_o}\right) = \mathbf{E}_\xi\{\text{BER}(\xi)\}\,, \quad (23)$$

where $\overline{E}_b$ is the average bit energy.

IV. Numerical Results

For this example we use $T_f = 160$ ns and two frequency shifts values of $\Delta_o = 0.1858$ and $\Delta_o' = 0.3708$ GHz, corresponding to the first and second zero crossing of the autocorrelation function, respectively. Without loss of generality we assume $\psi = 0$. For the Gaussian case we use $\alpha^2 = 1$ and $\beta = 0$.

For the multipath case we consider both line-of-sight (LOS) and not-line-of-sight (NLOS) scenarios. Similar to [20], the calculations for the multipath case are based on sample averages over the different realizations of $\alpha^2(\xi,+\Delta)$, $\alpha^2(\xi,-\Delta)$ and $\beta(\xi)$ considering a sample size of 200 for every distance D, and averaging the results over $D=3,6,9$ meters for LOS and $D=1,2,3$ meters for NLOS. Fig. 3 depicts histograms for $\alpha^2(\xi,+\Delta_o)$, $\alpha^2(\xi,-\Delta_o)$ and $\beta(\xi)$for $\Delta_o \simeq 0.1858$ GHz. Figs. 4(a) and 4(b) show the BER for $\Delta_o \simeq 0.1858$ and $\Delta_o' \simeq 0.3708$ GHz, respectively.

For reference we have included BER results for binary orthogonal PPM as calculated in [12].

V. Conclusions.

Given the huge bandwidth available for UWB, M-ary orthogonal signaling based on frequency modulation is an alternative for exchanging bandwidth for power

In this work we study ultra wideband (UWB) communications over dense multipath channels using binary frequency shift keying (FSK) data modulation. We take into account the effects of both the antenna system and the multipath channel.

Due to the antenna effects, both FSK signals are received with different (average) energy. In AWGN, this difference in

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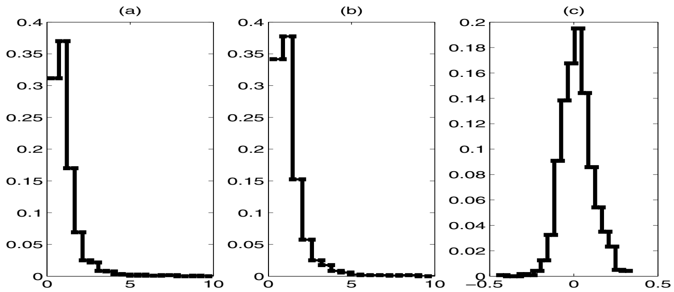

Fig. 3. Histograms calculated with $\Delta_o \simeq 0.1858$ for: (a) $\alpha^2(\xi, +\Delta_o)$, (b) $\alpha^2(\xi, -\Delta_o)$, and (c) $\beta(\xi)$. The ordinate represents appearance frequency, and the abscissa represents the value of the parameter.

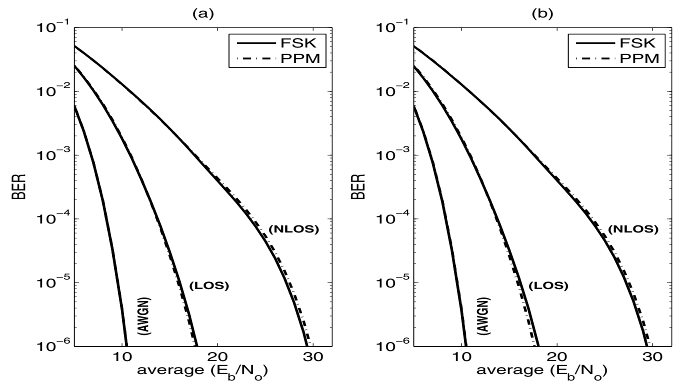

Fig. 4. BER vs. $\left(\frac{\overline{E}_b}{N_o}\right)$: (a) Using $\Delta_o \simeq 0.1858$, and (b) $\Delta_o' \simeq 0.3708$.

energy is

$$10 \log_{10} \left(\frac{f_c \underline{+} \Delta_o}{f_c} \right)^2 \simeq \underline{+} 0.3169 \text{ dB and } \underline{+} 0.6214 \text{ dB}$$

for $\Delta_o \simeq 0.1858$ GHz and $\Delta_o' \simeq 0.3708$ GHz, respectively.

Due to the frequency selectivity of the multipath channel, both FSK signals are received with different (random) energies.

For the type of signals and indoor office channel under consideration, these results in fig. 4 indicate the following:

- For BER $= 10^{-6}$, using $\Delta_o \simeq 0.1858$ GHz (the first zero crossing of $\gamma(2\Delta)$, corresponding to minimum shift MFSK), SNR loss is about $0.0, 0.2$, and -0.3 dB for AWGN, LOS and NLOS, respectively, when we use FSK instead of PPM .
- By increasing the frequency shift to $\Delta_o' \simeq 0.3708$ GHz (the second zero crossing of $\gamma(2\Delta)$), the SNR loss is about $0.0, 0.4$, and -0.3 dB for AWGN, LOS and NLOS, respectively.

These results show that by using an adjustable threshold T that depends on the received signal energies, the effects of the difference in energies in the BER is relatively minor. Hence, using MFSK results in a SNR degradation somewhat acceptable. Further studies need to be done using a fixed threshold, using M-ary FSK with large M or FSK combined with Frequency Hopping, and other antenna types.

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