**IEEE Vehicular Technology Conference, pp. 1654-1658, April 2003, Jeju, Korea**

# On the Performance of Bi-Phase Modulated UWB Signals in a Multipath Channel

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***Abstract* - The bi-phase modulation (BPM) for ultra-wide bandwidth (UWB) systems has some advantages over other modulation schemes such as a smoother power spectral density and higher resistance to jitter. In this paper, we estimated the BER performance of the BPM for two different data rates, 10 Mbps and 100 Mbps, in a multipath environment through simulation and compared the results with that for the pulse position modulation (PPM). Our results indicate that the BPM performs better than the PPM for both data rates. The BER performance is sensitive to the data rate for both modulation schemes, and the performance gap between the two data rates increases as the SNR increases.**

## I. INTRODUCTION

The UWB technology has drawn phenomenal interest in industry as well as academia since the Federal Communications Committee (FCC)'s allocation of UWB spectrum in February 2002. A UWB bandwidth is the frequency band bounded by the points that are 10 dB below the highest radiated emission of the complete transmission system including the antenna. The FCC definition of a UWB signal is such that the fractional bandwidth[1] is equal to or greater than 20 percents or the UWB bandwidth is equal to or greater than 500 MHz, regardless of the fractional bandwidth [1]. UWB uses extremely short duration pulses with the pulse width of a sub-nanosecond, instead of continuous waves, to transmit information.

UWB has several advantages over the conventional narrow band communication methods such as high data rate, low-power dissipation, robustness for multipaths, and resistance to interception. Since there is typically no carrier for the UWB signals, the RF circuit is potentially simpler. In addition, UWB offers the radar capability that can be applied for ranging, position location, imaging, see-through-wall, and other similar ones.

Various modulation schemes are possible for UWB signaling such as pulse position modulation (PPM), amplitude shift keying (ASK), on-off keying (OOK), phase shift keying (PSK), and frequency shift keying (FSK). ASK modulates the amplitude of a pulse, while OOK is a special case of ASK.

Ramirez-Mireles analyzed upper bounds of the BER performance for PPM under a multipath environment [2]. Welborn analyzed the performance of several UWB modulation schemes using a signal constellation and predicted the bi-phase modulation (BPM), precisely speaking binary phase shift modulation, would perform 3 dB better than that of other modulation schemes in Additive White Gaussian Noise (AWGN) environment [3]. Lee et al. estimated the performance of UWB communication systems through simulation under a deterministic two-ray path model and the Sale-Valenzuela model, respectively [4]. Recently, Cassioli et al. proposed a statistical UWB channel model based on actual measurements in a modern office building [5]. In this paper, we estimated the performance of the BPM under Cassioli's channel model for two different data rates and compared the results with that of the PPM.

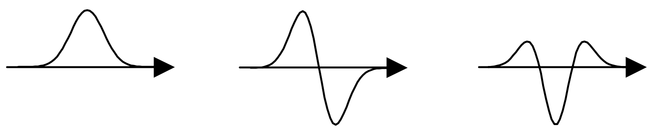
The paper is organized as follows. Section II describes UWB pulse types commonly used in practice and various modulation schemes. Section III covers Cassioli's channel model considered in our simulation, and Section IV presents our simulation results and observations made from the results. Section V concludes the paper.

## II. UWB PULSE CHARACTERISTICS AND MODULATION

Since a typical UWB system does not require a carrier, the pulse shape is an important design consideration and can affect the overall system performance. A desirable pulse shape should be easy for physical implementation and convenient for theoretical analysis. Gaussian pulses and their derivatives have

[1] A fractional bandwidth is defined as the ratio of the signal bandwidth to center frequency, $2(f_H-f_L)/(f_H+f_L)$.

been widely used due to the ease of mathematical modeling, and they are shown in Figure 1. *We assume that the radiated signal at the transmitter antenna is a Gaussian monocycle as shown in Figure 1 (b).*



(a) Gaussian (b) Gaussian Monocycle (c) Gaussian Doublet

Figure 1. Gaussian Pulses and Their Derivatives

A received UWB signal at the receiver side can be modeled as the derivative of the transmitted signal provided a certain condition is met [6]. The waveform of the received signal considered in this paper is the derivative of Gaussian monocycle, called Gaussian doublet, and is shown in Figure 1 (c).

A Gaussian monocycle is expressed as (1), where $A$ is the amplitude and $\tau$ is the duration between peak-to-peak [7]:

$$p(t) = -2\sqrt{e}A\left(\frac{t}{\tau}\right)exp\left(-2\left(\frac{t}{\tau}\right)^2\right) \qquad (1)$$

The power spectral density (PSD) of a Gaussian monocycle with A=1 and $\tau$=47.5 ps is shown in Figure 2. Note that the center frequency of the spectrum is about 6.7 GHz, which is close to the center of the spectrum allocated for UWB, 3.1 GHz to 10.6 GHz. *A Gaussian monocycle with the width $\tau$=47.5 ps is used for our simulation*.

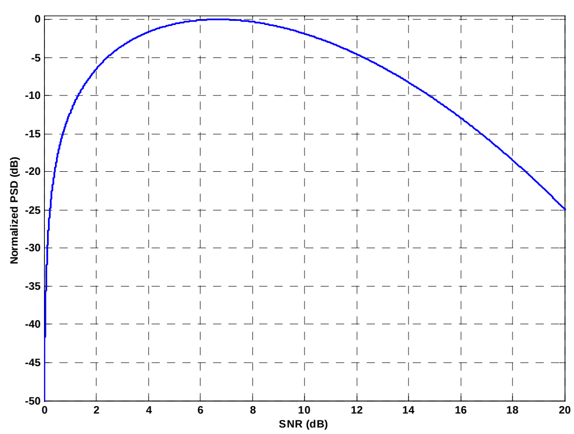
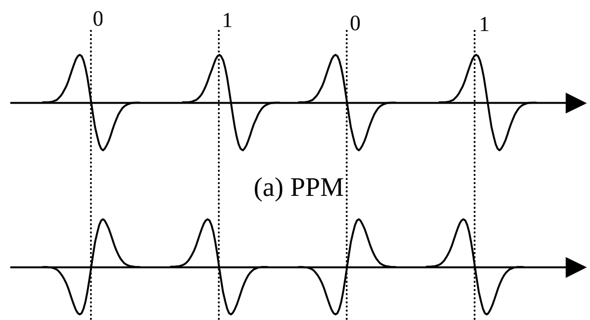



Figure 2. Power Spectral Density of a Gaussian Monocycle

The data considered in our simulation is unbiased binary random sequences with the data rates of 10 Mbps and of 100 Mbps. Gaussian monocycles modulated for the data sequence under the PPM and the BPM are shown in Figure 3. A pulse position is delayed by 62.5 ps for a data bit 1 under the PPM for both data rates, while the BPM is simply an antipodal signaling scheme.

The power spectral densities of the two modulated signals in Figure 3 are shown in Figure 4. The envelope of the two power spectral densities is identical to that of a single Gaussian monocycle. However, both of the power spectral densities have narrow line spectral components due to the repetition of the pulses at a given data rate. Line spectral components are undesirable, since it reduces the amount of radiated power for the same peak power (which is usually regulated by government).




(a) PPM

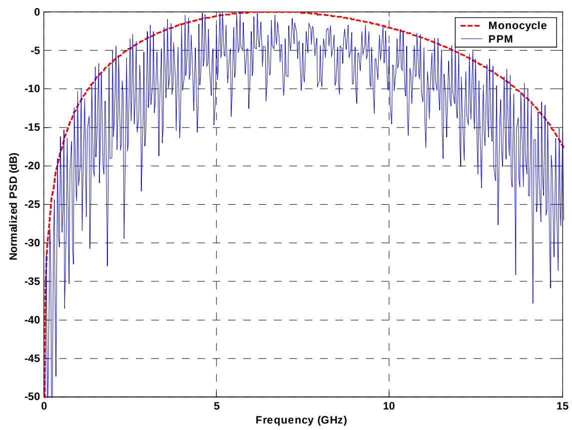
(b) BPM

Figure 3. The PPM and the BPM of Gaussian Monocycles

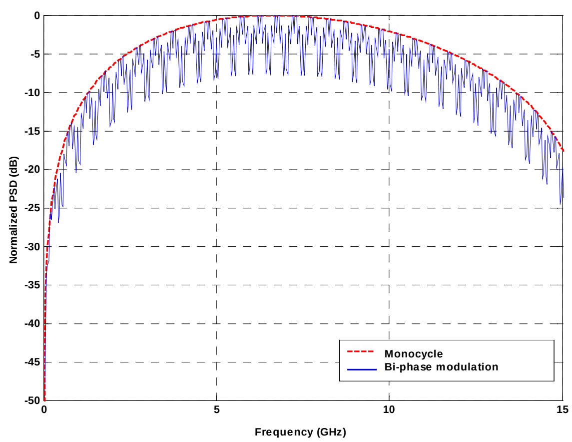
As can be seen from Figure 4, line spectral components of the BPM are weaker than that for the PPM, and, hence, the BPM has a more desirable power spectral density. It should be noted that power spectral density of the PPM can be improved through the time hopping or dithering of pulses at the cost of higher circuit complexity.

## III. CHANNEL MODEL

Narrowband channel models such as Sale-Valenzuela model are inadequate for a UWB system due to the coarse resolution of multipaths. UWB channel models were investigated in [5],[8],[9]. Cassioli, Win, and Molisch proposed a stochastic tapped-delay-line (STDL) model for a UWB indoor channel based on actual measurements [5]. The model consists of large-scale and small-scale fading statistics. The large-scale fading characterizes changes of the received signal under a significant change in the transmitter-receiver (T-R) distance, while the small-scale statistics concerns relatively small changes in the T-R distance. We adopted power delay profiles (PDPs) based on the large-scale fading statistics for our simulation.




(a) PPM




(b) BPM

Figure 4. PSD of Gaussian Monocycle Pulses

The large-scale fading statistics of the STDL model requires three parameters for a given T-R distance, the total average energy gain, the excess decay time, and the power ratio. A path loss is obtained according to the dual slope model whose break point of the T-R distance is 11 m. The total average energy gain is obtained from a lognormal shadowing with the mean of a negative path loss and the standard deviation of 4.3 dB. The excess decay time follows the lognormal distribution with the mean of 16.1 dB (in the unit of nanosecond) and the standard deviation of 1.27 dB. The power ratio specifies the ratio of the average energy gain in the first delay bin to that of the second delay bin and is used to compute the energy gain of the second delay bin. The energy gains of the subsequent delay bins decay exponentially with the excess decay time. For details, refer to [5].

We set the delay bin width of 2 ns in our simulation, which implies existence of at most one multipath for each delay bin of 2 ns. An observation window reflects the time for a significant decay of multipaths, which is determined by the excess decay time. In this paper, the observation window is set to five times the excess decay time as suggested in [5]. A typical observation time is about 200 ns for our simulation runs, which implies as many as 100 multipath signals.

Figure 5 shows an average large-scale PDP (in the dB scale) of 10,000 channels obtained using the STDL model with the following parameters; the T-R distance of 10 m, the delay bin width of 2 ns, the average excess decay time of 42.83 ns, the average power ratio of 0.5049, and the average number of bins of 107.08, and the average maximum excess delay of 214.15 ns. The power level of the first delay bin is highly related to the T-R distance, while those of the remaining bins decay exponentially.

A received signal is constructed using a superposition of attenuated and delayed Gaussian doublets according to a PDP obtained from the STDL model. Then, a convolution operation is performed between the received signal and a template, which is a Gaussian doublet. The convolution operation is essentially a matched filter operation commonly adopted in digital communications [10]. The resultant value is hard decided to estimate the binary data sent. Since the displacement of a pulse for a bit 1 under the PPM is 62.5 ps for our system, the sampling rate for received input signals is set to 32 GHz in our simulation to resolve the displacement.

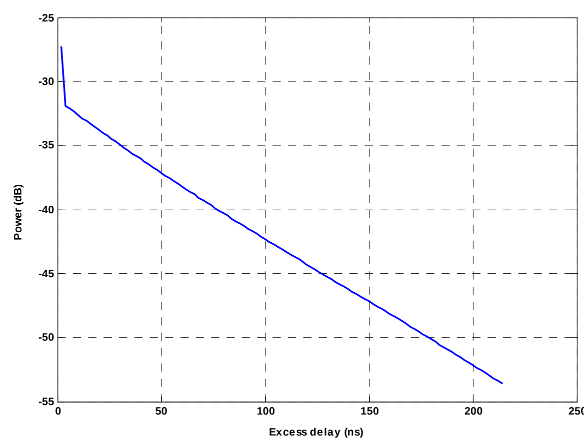



Figure 5. A Large-Scale PDP

Finally, the SNR value of a received pulse is computed within the observation period. An observation period should be sufficiently large, so that the signal energy outside the observation period is negligible. Since multipaths may exist for about 200 ns for our model, the observation period for our simulation is set to the pulse repetition period, i.e., 100 ns for the data rate of 10 Mbps and 10 ns for 100 Mbps. In other words, SNR values are computed for the entire interval of the two consecutive pulses. It should be noted that the intersymbol interference exists for both the data rates, as the observation period is less than the maximum excess delay time of pulses.

## IV. Simulation Results

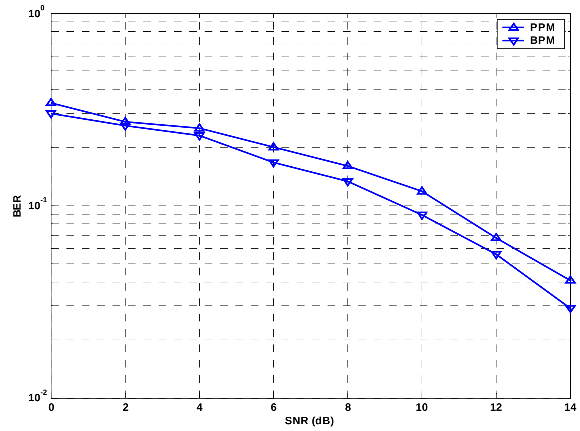
We modeled the entire UWB system including pulse generation, the channel model, and the receiver in Matlab. The goal of our simulation is two fold. The first objective is to verify the superiority of the BPM over the PPM as predicted by Welborn [3]. The second one is to investigate the impact of the data rate on the BER performance.

The simulation environment is summarized as follows. The T-R distance is set to 10 m, and the STDL channel with AWGN is employed. Gaussian monocycle pulses with the peak-to-peak time of $\tau$=47.5 ps and pulse repetition period of 10 ns (for the data rate of 100 Mbps) or 100 ns (for 10 Mbps) are radiated from the transmitting antenna. The number of multipaths (i.e., the delay bins), which varies from one simulation to another, is around 100. A new channel is created after every 10 bits of binary data.

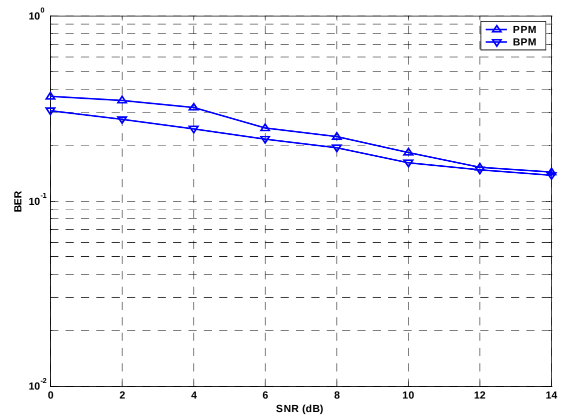
Monte Carlo error counting method was adopted for estimation of the BER performance for both the BPM and the PPM. The Monte Carlo simulation was performed for the confidence level of 90 percents within the error range of 10 percents. For example, since the required number of errors for the given confidence level and the accuracy is 271, the number of simulation runs required is 2,710 (=271/0.1) for the BER of 0.1 and 271,000 (=271/0.001) for the BER of 0.001.

The BER performance of the PPM and the BPM at the two different data rates are shown in Figure 6. As predicted, the BPM performs better than the PPM for the entire range of the SNR and for both the data rates. However, the difference is small for the data rate of 100 Mbps, especially for a high SNR value. As the SNR increases, the difference in performance for the two modulation schemes increases for the data rate of 10 Mbps. In contrast, the difference decreases for 100 Mbps as the SNR increases. Note that the performance of the two modulations is nearly the same for 100 Mbps in the high SNR range, which may be due to the dominance of the intersymbol interference. So the BPM is more advantageous than the PPM, especially for the case with a low SNR and a high data rate.

The BPM is about 1.19 dB better than the PPM at the BER of $2\times10^{-1}$ for the data rate of 10 Mbps, while the performance gap is slightly increased to 1.62 dB for 100 Mbps. The simulation results indicate that an earlier prediction made in [3], which expects 3 dB better performance for the BPM, is too optimistic. The main reason for the deviation is believed due to the failure of consideration of multipaths for [3].




(a) Date Rate of 10 Mbps



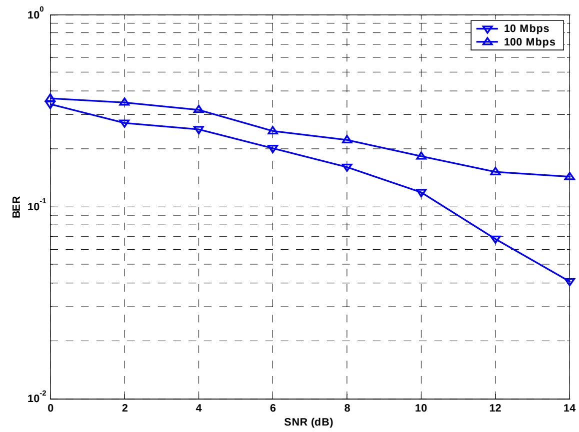

(b) Data Rate of 100 Mbps

Figure 6. BER Performance of the PPM and the BPM

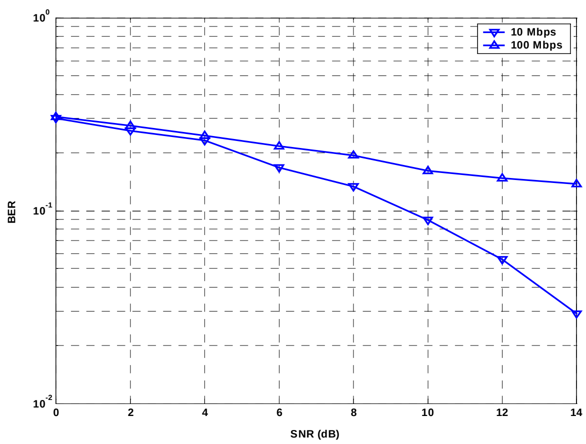
Figure 7 compares the BER performance of the PPM and the BPM for the two different data rates. Both the modulation schemes show the same trend; the performance of 10 Mbps is better than that for 100 Mbps, and the gap becomes wider for higher SNR values. Again, the relatively poor performance of 100 Mbps, even for a higher SNR value, seems due to the dominance of the intersymbol interference.

## V. Conclusion

The bi-phase modulation (BPM) for UWB systems has some advantages over other modulation schemes such as a smoother power spectral density and higher resistance to jitter. Welborn predicted that the BPM would perform better than




(a) PPM




(b) BPM

Figure 7. BER Performance of Data Rates

the PPM by 3 dB based on the analysis of a signal constellation [3].

In this paper, we estimated the BER performance of the BPM for UWB signals for two different data rates, 10 Mbps and 100 Mbps, through simulation in a multipath environment adopted from the channel model of Cassioli et al. and compared the results with that for the PPM. Our results can be summarized as following.

a) The BPM performs better than the PPM for both the data rates for the entire SNR range experimented. The difference in performance between the two modulation schemes increases as the SNR increases for the data rate of 10 Mbps. In contrast, the gap decreases for the 100 Mbps as the SNR increases, and there is practically no difference for a high SNR value.

b) The BER performance is sensitive to the data rate for both modulation schemes, and the performance gap between the two data rates increases as the SNR increases.

Finally, although the BPM seems more favorable than the PPM, other factors such as circuit complexity and multiple access should also be considered to select an adequate modulation scheme for one's application.

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