Performance of DPPAM UWB Communication Systems over Indoor Fading Channels

Tingting Lu and Hao Zhang
Dept. of Electrical and Computer Engineering
Ocean University of China, Qiangdao, China

T. Aaron Gulliver
Dept. of Electrical and Computer Engineering
University of Victoria, Victoria BC Canada

***Abstract*—Differential pulse position amplitude modulation (DPPAM) is considered in an ultra wideband (UWB) communication system. DPPAM combines differential pulse position modulation (DPPM) and pulse amplitude modulation (PAM) to provide good performance with low computational complexity. The DPPAM UWB signal is derived from that of pulse position amplitude modulation (PPAM). The frame error rate (FER) of *MN*-ary DPPAM systems over additive white Gaussian noise (AWGN) and indoor fading channels is analyzed. The results show that the FER performance with 2*N*-ary DPPAM is better than that with 2*N*-ary DPPM and PPM, and *MN*-ary (*M*>2) DPPAM provides a good compromise between FER and complexity.**

Keywords- DPPM; PPAM; Indoor fading channels; UWB

I. INTRODUCTION

Ultra wideband (UWB) communications has attracted much attention in recent years for indoor short range, high data rate wireless applications. UWB impulse radio systems transmit information using extremely short pulses on a nanosecond time scale [1]. Pulse amplitude modulation (PAM) and pulse position modulation (PPM) are commonly used in UWB systems. The error probability and capacity of PPM and PAM have been investigated in [2],[3],[4]. Recently, a new modulation scheme called pulse position amplitude modulation (PPAM) has been proposed [5]. PPAM is a combination of PPM and PAM which provides a good tradeoff between system performance and computational complexity. In particular, a 2*N*-ary PPAM UWB system has better performance than a 2*N*-ary PPM system with only half the computational complexity. DPPM has also been proposed as an alternative to PPM [6], [7].

DPPM provides a higher transmission capacity by deleting redundant timeslots in a frame. It does not require symbol synchronization since each frame is initiated with a '1' pulse. Much of the research on DPPM systems has been for optical communication systems. In [8], the properties and spectral characteristics of a type of DPPM called digital pulse interval modulation (DPIM) are discussed. The probability of error with DPIM over optical wireless communication systems was also presented. In [9], the packet error rate (PER) was derived for a simple threshold detection based receiver. It was shown that the PER of DPPM for a given average received irradiance is superior to that with on-off keying (OOK), but PPM is better than DPPM. A hybrid modulation technique for optical communications called differential amplitude pulse-position modulation (DAPPM) was recently proposed in [10]. DAPPM is a combination of PAM and DPPM. The symbol structure and properties of DAPPM, e.g., peak-to-average power ratio (PAPR), bandwidth requirements, and throughput, were compared with other techniques such as DPIM.

This paper considers DPPAM for UWB systems. The format of a DPPAM signal in a UWB system is derived. The probability of error over AWGN and indoor fading channels is derived. In order to make the results easy to analyze, a simple upper bound on the symbol error rate is also introduced.

The remainder of the paper is organized as follows. In Section II, DPPAM signal construction and the system model are described. The error probability of DPPAM over AWGN and indoor fading channels is given in Section III. A simple upper bound on the probability of error is also provided. Numerical results are presented in Section IV. Finally, Section V provides some conclusions.

II. SIGNAL CONSTRUCTION AND SYSTEM MODEL

An *MN*-ary DPPAM signal is given by an N_i-dimensional vector with nonzero value in the N_ith dimension

$$\mathbf{s}_{mN_i} = \left[0, \ldots, 0, A_m\sqrt{E_g}\right] \tag{1}$$

where $1 \le N_i \le N$, $1 \le m \le M$, and $A_m\sqrt{E_g}$ is the PAM amplitude with $A_m = 2m-1-M$, E_g is the energy of the signal pulse, $E_g = 3E_{av}/(M^2-1)$, and E_{av} is the average signal energy. A DPPAM symbol is obtained from the corresponding PPAM symbol by deleting the redundant '0' timeslots, as shown in Table 1. In contrast to *MN*-ary PPAM where a symbol has fixed length *N*, DPPAM has variable length symbols.

Table 1. Symbol Mapping for 8PPM, 8PPAM and 8DPPAM

	8PPM		2×4 PPAM		2×4 DPPAM		4×2DPPAM	
a	Symbol B	Length λ	Symbol B	Length λ	Symbol B	Length $\lambda = a \bmod(4)+1$	Symbol B	Length $\lambda = a \bmod(2)+1$
0	00000001	8	0001	4	1	1	1	1
1	00000010	8	0010	4	10	2	10	2
2	00000100	8	0100	4	100	3	2	1
3	00001000	8	1000	4	1000	4	20	2
4	00010000	8	0002	4	2	1	3	1
5	00100000	8	0020	4	20	2	30	2
6	01000000	8	0200	4	200	3	4	1
7	10000000	8	2000	4	2000	4	40	2

978-1-4673-1881-5/12/$31.00 ©2012 IEEE

The jth MN-ary DPPAM symbol B_j has a length determined by the data being encoded, i.e., $\lambda_j = a_j$ (mod N)+1. The cumulative length Λ_j in DPPAM is defined as

$$\Lambda_j = \begin{cases} \sum_{k=0}^{j-1} \lambda_k & j > 0 \\ 0 & j = 0 \end{cases}, \tag{2}$$

thus, $\Lambda_j T$ represents the beginning of the jth symbol, where T is the timeslot duration.

Ignoring time-hopping, the MN-ary DPPAM signal can be expressed as

$$s(t) = \sum_{j=-\infty}^{\infty} A_m \sqrt{E_g}\, p\left(t - \Lambda_j T - \lambda_j T\right) \tag{3}$$

where $p(t)$ is the UWB pulse of duration T_p. The received signal can be modeled as the derivative of the transmitted pulses assuming propagation in free space [1]

$$r(t) = \sum_{j=-\infty}^{\infty} A_m \sqrt{E_g}\, q\left(t - \Lambda_j T - \lambda_j T\right) + w(t) \tag{4}$$

where $w(t)$ is additive white Gaussian noise (AWGN) with power spectral density $N_0/2$, and $q(t)$ is the received pulse waveform. For N-dimensional orthogonal signals, the optimal receiver is an N-ary correlation receiver followed by a detector. For an MN-ary DPPAM UWB system, N cross-correlators are required for demodulation which is the same as for the MN-ary PPAM UWB system in [5]. Compared with an MN-ary PPM UWB system, which requires MN cross-correlators, the demodulation complexity is much lower.

A. Statistical Model for UWB Indoor Fading Channels

The time-varying UWB indoor propagation channel can be described by the impulse response of the channel as [11]

$$h(t) = \sum_{l=1}^{L} a_l(t)\delta(t - \tau_l(t)) \tag{5}$$

where t is the observation time, L is the number of resolvable multi-path components, $\tau_l(t)$ is the arrival time of the received signal which is log-normal distributed, $a_l(t)$ is the random time-varying amplitude attenuation, and δ denotes the Dirac delta function. Without loss of generality, we assume $\tau(t)=(l-1)\tau$, where $\tau=1/W$ and W is the signal bandwidth. In a UWB system, the number of scatters within one resolvable path is only on the order of 2 or 3 [11]. Since this number is too small to apply the central limit theorem, the distribution of $a_l(t)$ cannot be modeled as Gaussian. Although the exact distribution of $a_l(t)$ is difficult to derive, several models have been proposed [11], [12] considering that a small number of scatterers best describes the indoor wireless channel. In [11], a stochastic tapped delay line (STDL) propagation model was derived from experimental data. It was shown that the Nakagami distribution is the best fit for the indoor small-scale magnitude statistics. $a_l(t)$ can be expressed as $a_l(t) = v_l a_l$ where $v_l = \text{sign}(a_l)$ and $a_l = |a_l(t)|$ is the amplitude of $a_l(t)$. The PDF of the amplitude a_l is given by [11]

$$p(a_l) = \frac{2}{\Gamma(m)}\left(\frac{m}{\Omega_l}\right)^m a_l^{2m-1} e^{-m a_l^2/\Omega} \tag{6}$$

where $\Gamma(\ )$ denotes the Gamma function, $\Omega=\text{E}[a^2]$, and $m=\text{E}[a^2]/\text{var}[a^2]$ with $m\geq 1/2$. To make the channel characteristics analyzable without affecting the generality of the channel, we further define v_l as a random variable that takes the values +1 or -1 with equal probability.

B. Error Probability of DPPAM UWB Systems

The received signal is

$$\mathbf{r} = \mathbf{s} + \mathbf{w}, \tag{7}$$

where $\mathbf{s}$ is the transmitted signal and $\mathbf{w}$ is AWGN. To evaluate the error probability of MN-ary DPPAM, suppose that $\mathbf{s}_{mN_i}$ is transmitted, $1\leq N_i \leq$ N, $1\leq m \leq M$, which is defined as a N_i-dimensional vector with nonzero value in the N_ith dimension $\mathbf{s}_{mN_i} = \left[0, \ldots, 0, A_m\sqrt{E_g}\right]$

The received signal over an AWGN channel is then

$$\mathbf{r} = \left[n_1, n_2, \ldots, A_m\sqrt{E_g} + n_{N_i}\right],$$

where $n_1, n_2, \ldots, n_{N_i}$ are zero-mean, mutually statistically independent Gaussian random variables with equal variance $N_0/2$.

Let $\mathbf{h}_j$, $1\leq j\leq N$, denote the basis signal vector given by

$$\mathbf{h}_j = [0, \ldots, 0, 1, 0, \ldots, 0], \tag{8}$$

where the nonzero value is in the jth dimension. The optimum detector decides in favor of the signal corresponding to the correlator

$$C(\mathbf{r}, \mathbf{h}_j) = \mathbf{r}\cdot\mathbf{h}_j = \sum_{i=1}^{N} r_i h_{ji},\ j = 1, 2, \ldots, N, \tag{9}$$

with the minimum Euclidean distance. The correlators outputs are given by

$$\begin{aligned} C(\mathbf{r}, \mathbf{h}_1) &= n_1 \\ C(\mathbf{r}, \mathbf{h}_2) &= n_2 \\ \cdots &\quad \cdots \\ C(\mathbf{r}, \mathbf{h}_{N_i}) &= A_m\sqrt{E_g} + n_{N_i} \\ C(\mathbf{r}, \mathbf{h}_{N_i+1}) &= 0 \\ \cdots &\quad \cdots \\ C(\mathbf{r}, \mathbf{h}_N) &= 0 \end{aligned} \tag{10}$$

With the optimum detector, the demodulated signal is

$$\hat{\mathbf{s}} = \arg\min_{\mathbf{s}_{ij}} \left\| C\left(\mathbf{r}, \mathbf{h}_j\right) - A_i\sqrt{E_g} \right\|, \quad i = 1, \ldots, M,\ j = 1, \ldots, N \tag{11}$$

Assuming $\mathbf{s}_{mN_i}$ was sent, the optimum detector decides on the nonzero dimension, i.e. N_i, in favor of the dimension corresponding to the largest correlator magnitude given in (9). This is used to decide which of the M possible amplitudes, i.e.

m, has been transmitted. According to this decision rule, the average probability of a correct decision is given by

$$P_c = \frac{1}{M}\left(\begin{array}{l} \sum_{m=2}^{M-1}\int_{(A_m-1)\sqrt{E_g}}^{(A_m+1)\sqrt{E_g}}\left(\frac{1}{\sqrt{2\pi}}\int_{-r_m/\sqrt{N_0/2}}^{r_m/\sqrt{N_0/2}} e^{-x^2/2}dx\right)^{N_i-1} p(r_m)dr_m \\ +\int_{-\infty}^{(A_m+1)\sqrt{E_g}}\left(\frac{1}{\sqrt{2\pi}}\int_{-r_m/\sqrt{N_0/2}}^{r_m/\sqrt{N_0/2}} e^{-x^2/2}dx\right)^{N_i-1} p(r_m)dr_m\Bigg|_{m=1} \\ +\int_{(A_m-1)\sqrt{E_g}}^{+\infty}\left(\frac{1}{\sqrt{2\pi}}\int_{-r_m/\sqrt{N_0/2}}^{r_m/\sqrt{N_0/2}} e^{-x^2/2}dx\right)^{N_i-1} p(r_m)dr_m\Bigg|_{m=M} \end{array}\right), \tag{12}$$

where

$$p(r_m) = \frac{1}{\sqrt{\pi N_0}}\exp\left(-\frac{\left(r_m - A_m\sqrt{E_g}\right)^2}{N_0}\right) \tag{13}$$

The probability of a symbol error for MN-ary DPPAM is then

$$P_e = 1 - P_c. \tag{14}$$

In DPPAM systems, the pulses define the symbol boundaries, so an error is not confined to the symbol in which it occurs. Consider a frame of data encoded using DPPAM. A pulse detected in the wrong slot would affect symbols on either side of the pulse, but would have no influence on the remaining symbols in the frame. A pulse not detected or detecting an additional pulse would result in a shift of the remaining symbols in the frame. Thus, unlike PPM and PPAM, the error probability of DPPAM cannot easily be expressed as a bit or symbol error rate. In order to compare the performance of DPPAM with PPM and PPAM schemes, the analysis is based on the frame error rate (FER). A frame is considered to be in error if one or more symbols within the frame are in error. The frame error probability can be expressed as [9]

$$P_{FE} = 1 - \prod_{i=1}^{N_s}\left(1 - P_{e_i}\right) \tag{15}$$

where N_s is the number of symbols in a frame and P_{e_i} is the probability that the ith symbol in the frame is in error.

Since the probability of error based on (12), (13) and (14) is complex and must be evaluated via numerical integration for large M, a simple upper bound on the symbol error probability is employed [13]. Assuming an equiprobable MN-ary DPPAM constellation, an upper bound on the error probability of a DPPAM signal over an AWGN channel can be obtained as

$$P_{e|s_{mN_i}} \le P\left(\begin{array}{l}\left(\bigcup_{j=1}^{N_i-1}\left|\mathrm{C}\left(\mathbf{r},\mathbf{h}_j\right)\right| > \left|\mathrm{C}\left(\mathbf{r},\mathbf{h}_{N_i}\right)\right|\right) \\ \bigcup\left(\left|\mathrm{C}\left(\mathbf{r},\mathbf{h}_{N_i}\right) - A_m\sqrt{E_g}\right|\right) > \sqrt{E_g}\end{array}\right). \tag{16}$$

Considering the union bound of the N_i-1 events in the second term of (16) gives

$$\begin{aligned} P_{e|s_{mN_i}} &\le P\left(\left(\bigcup_{j=1}^{N_i-1}\left|\mathrm{C}\left(\mathbf{r},\mathbf{h}_j\right)\right| > \left|\mathrm{C}\left(\mathbf{r},\mathbf{h}_{N_i}\right)\right|\right)\bigcup\left(\left|n_{N_i}\right| > \sqrt{E_g}\right)\right) \\ &\le \sum_{j=1}^{N_i-1} P\left(\left|\mathrm{C}\left(\mathbf{r},\mathbf{h}_j\right)\right| > \left|\mathrm{C}\left(\mathbf{r},\mathbf{h}_{N_i}\right)\right|\right) + P\left(\left|n_{N_i}\right| > \sqrt{E_g}\right) \\ &= \left[\begin{array}{l}\left(N_i - 1\right)P\left(\left|\mathrm{C}\left(\mathbf{r},\mathbf{h}_j\right)\right| > \left|\mathrm{C}\left(\mathbf{r},\mathbf{h}_{N_i}\right)\right|\right) \\ +P\left(\left|n_{N_i}\right| > \sqrt{E_g}\right)\end{array}\right]_{1\le j\le N_i-1} \end{aligned} \tag{17}$$

Given $\mathrm{C}(\mathbf{r},\mathbf{h}_j)$, j=1,…,N_i-1, as in (9), it can be shown that

$$P\left(\left|\mathrm{C}\left(\mathbf{r},\mathbf{h}_j\right)\right| > \left|\mathrm{C}\left(\mathbf{r},\mathbf{h}_{N_i}\right)\right|\right) = 2Q\left(\left|A_m\right|\sqrt{\frac{E_g}{N_0}}\right) \tag{18}$$

$$P\left(\left|n_{N_i}\right| > \sqrt{E_g}\right) = 2Q\left(\sqrt{\frac{2E_g}{N_0}}\right). \tag{19}$$

Assuming all DPPAM signals are equally likely a priori, the upper bound on the symbol error probability for MN-ary DPPAM is

$$P_e < \frac{N_i-1}{M}\sum_{m=1}^{M} 2Q\left(\left|A_m\right|\sqrt{\frac{3E_{av}}{(M^2-1)N_0}}\right) + 2Q\left(\sqrt{\frac{6E_{av}}{(M^2-1)N_0}}\right) \tag{20}$$

Since an error can only occur in one direction when either of ±(M-1) is transmitted, a tighter bound is given by

$$\begin{aligned} P_e &< \frac{N_i-1}{M}\sum_{m=1}^{M} 2Q\left(\left|A_m\right|\sqrt{\frac{3E_{av}}{(M^2-1)N_0}}\right) + \frac{2(M-1)}{M}Q\left(\sqrt{\frac{6E_{av}}{(M^2-1)N_0}}\right) \\ &= \frac{N_i-1}{M}\sum_{m=1}^{M} 2Q\left(\left|A_m\right|\sqrt{\frac{3}{(M^2-1)}\rho_s}\right) + \frac{2(M-1)}{M}Q\left(\sqrt{\frac{6}{(M^2-1)}\rho_s}\right). \end{aligned} \tag{21}$$

where $\rho_s=E_{av}/N_0$ is the symbol SNR.

The upper bound on the error probability of the corresponding DPPM signal over an AWGN channel is [14]

$$\begin{aligned} P_{e|s_{MN_i}} &\le P\left(\bigcup_{j=1}^{MN_i-1}\left|C\left(\mathbf{r},\mathbf{h}_j\right)\right| > \left|C\left(\mathbf{r},\mathbf{h}_{MN_i}\right)\right|\right) \\ &\le \sum_{j=1}^{MN_i-1} P\left(\left|C\left(\mathbf{r},\mathbf{h}_j\right)\right| > \left|C\left(\mathbf{r},\mathbf{h}_{MN_i}\right)\right|\right) \\ &= \left[\left(MN_i-1\right)P\left(\left|C\left(\mathbf{r},\mathbf{h}_j\right)\right| > \left|C\left(\mathbf{r},\mathbf{h}_{MN_i}\right)\right|\right)\right]\Big|_{\forall j\ne MN_i} \\ &= \left(MN_i-1\right)Q\left(\sqrt{\rho_s}\right) \end{aligned} \tag{22}$$

This gives for PPM [13]

$$P_e \le (MN-1)Q\left(\sqrt{\rho_s}\right) \tag{23}$$

C. Error Probability of MN-ary DPPAM over Indoor Fading Channels

Apart from AWGN, the transmitted signal suffers from fading. We employ equal gain combining (EGC) at the receiver, so (4) can be written as

$$r(t)=\sum_{l=1}^{L}\left(a_l(t)\delta\left(t-\tau_l(t)\right)X(t)+w(t)\right) \qquad (24)$$

where $X(t)=s'(t)=\sum_{j=-\infty}^{\infty} A_{mi}\sqrt{E_g}\,q\left(t-\Lambda_j T-\alpha_j T\right)$

The equivalent instantaneous SNR of the signal in (24) is given by [14]

$$\rho=\frac{\int_{-\frac{W}{2}}^{\frac{W}{2}} G_X(f)\left|H(f)\right|^2 df}{N_0 W}, \qquad (25)$$

where $G_x(f)$ is the power spectral density (PSD) of the UWB signal determined by the pulse shape and modulation employed, and $H(f)$ is the PSD of $h(t)$ given by

$$H(f)=v_l a_l e^{-j2\pi f(l-1)\tau}.$$

Without loss of generality, we assume $X(t)$ has a uniformly distributed PSD, i.e.

$$G_x(f)=\begin{cases}\dfrac{P_x}{W} & \text{where } f\in\left[-\dfrac{W}{2},\dfrac{W}{2}\right],\\ 0 & \text{otherwise}\end{cases} \qquad (26)$$

where P_x is the power of the received UWB signal. Equation (25) can then be written as

$$\rho=\rho_s\frac{1}{\pi}\int_0^{\pi}\left[\left(v_l a_l\cos((l-1)u)\right)^2+\left(v_l a_l\sin((l-1)u)\right)^2\right]du \qquad (27)$$

where $\rho_s=P_x/(WN_0)$ is the symbol SNR of the UWB system over an AWGN channel. The equivalent SNR ρ is given by the symbol SNR modified according to the number of paths and the fading coefficients.

The error probability of MN-ary DPPAM over an AWGN channel (14) can be expressed as

$$P_e=1-\frac{1}{M}\left(\begin{aligned}&\sum_{m=2}^{M-1}\frac{1}{\sqrt{2\pi}}\int_{(A_m-1)\sqrt{\frac{6}{M^2-1}\rho_s}}^{(A_m+1)\sqrt{\frac{6}{M^2-1}\rho_s}}\left(\frac{1}{\sqrt{2\pi}}\int_{-y}^{y}e^{-x^2/2}dx\right)^{N_i-1}e^{-\frac{\left(y-A_m\sqrt{\frac{6}{M^2-1}\rho_s}\right)^2}{2}}dy\\&+\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{(A_m+1)\sqrt{\frac{6}{M^2-1}\rho_s}}\left(\frac{1}{\sqrt{2\pi}}\int_{-y}^{y}e^{-x^2/2}dx\right)^{N_i-1}e^{-\frac{\left(y-A_m\sqrt{\frac{6}{M^2-1}\rho_s}\right)^2}{2}}dy\Bigg|_{m=1}\\&+\frac{1}{\sqrt{2\pi}}\int_{(A_m-1)\sqrt{\frac{6}{M^2-1}\rho_s}}^{+\infty}\left(\frac{1}{\sqrt{2\pi}}\int_{-y}^{y}e^{-x^2/2}dx\right)^{N_i-1}e^{-\frac{\left(y-A_m\sqrt{\frac{6}{M^2-1}\rho_s}\right)^2}{2}}dy\Bigg|_{m=M}\end{aligned}\right). \qquad (28)$$

where $y=r_m/\sqrt{N_0/2}$ and $\rho_s=E_{av}/N_0$.

With a simple variable transformation, the error probability of MN-ary DPPAM over indoor fading channels can be obtained by substituting ρ for ρ_s in (28). The upper bound on the error probability for an MN-ary DPPAM system over an AWGN channel given in (21) can then be employed for indoor fading channels giving

$$P_e<\frac{N_i-1}{M}\sum_{m=1}^{M}2Q\left(\left|A_m\right|\sqrt{\frac{3}{(M^2-1)}\rho}\right)+\frac{2(M-1)}{M}Q\left(\sqrt{\frac{6}{(M^2-1)}\rho}\right). \qquad (29)$$

The probability of frame error is given by (15).

IV. Performance Results

In this section, some performance results are presented to illustrate and verify the probability of error expressions obtained previously. Monte Carlo simulation is employed.

Figure 1 compares the FER for 2×N-ary DPPAM, DPPM and PPM over an AWGN channel with a frame length of 128 bits. When N=1, DPPAM is the same as PAM. Note that the simulation results for 2×1-ary DPPAM coincide with the theoretical results for binary PAM. This figure shows that 2×N-ary DPPAM is superior to DPPM and PPM in terms of FER performance. For 2×2-ary DPPAM, there is almost a 0.7 dB gain over PPM and a 0.2 dB gain over DPPM at a FER of 10^{-2}. However, this superiority decreases with increasing N. According to Fig. 1, 2×4-ary DPPAM has little advantage over 8-ary DPPM in terms of FER, but it is still better than 8-ary PPM.

Figure 2 compares the FER with M×2-ary DPPAM, DPPM and PPM over an AWGN channel with a frame length of 128 bits. This shows that the performance of DPPAM falls dramatically with increasing M. For 8-ary DPPM, there is almost a 6 dB gain over DPPAM at an FER of 10^{-2}. It can be seen that when M>2, DPPAM is not a good choice in terms of FER.

Figure 3 shows the frame error rate for M×2-ary DPPAM, DPPM and PPM over Nakagami fading channels with a frame length of 128 bits, m=3, and L=1. 2×2-ary DPPAM also has a superior FER over Nakagami fading channels, but the error probability of DPPAM deteriorates rapidly when M>2. For 16-ary DPPM, there is almost a 10 dB gain over 8×2-ary DPPAM at a FER of 10^{-2}. The curves were obtained by substituting ρ for ρ_s in the expression for AWGN channels.

V. Conclusions

The error probability of differential pulse position amplitude modulation (DPPAM) systems has been studied. Both AWGN and indoor fading channels were considered. The FER performance was first derived for an AWGN channel and then extended to Nakagami fading channels by averaging the SNR. It was shown that a 2×N-ary DPPAM is superior to 2×N-ary DPPM and 2×N-ary PPM over AWGN and Nakagami fading channels with only half the computational complexity. The FER performance of an MN-ary DPPAM system deteriorates rapidly with increasing M.

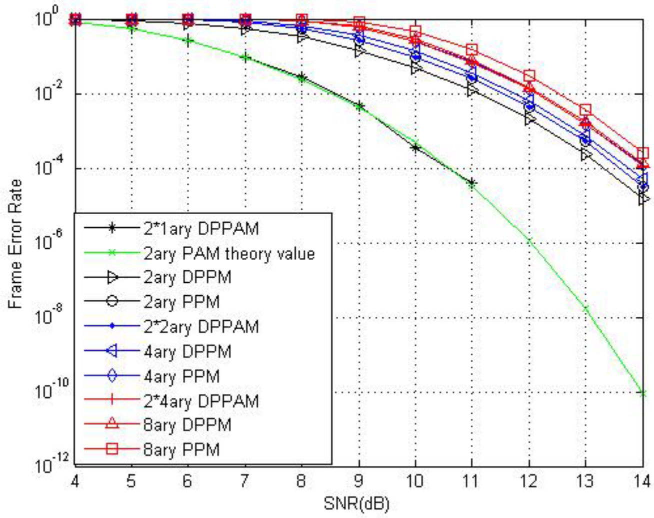

Figure 1: Frame error rate for 2×N-ary DPPAM, DPPM and PPM over an AWGN channel with a frame length of 128 bits.

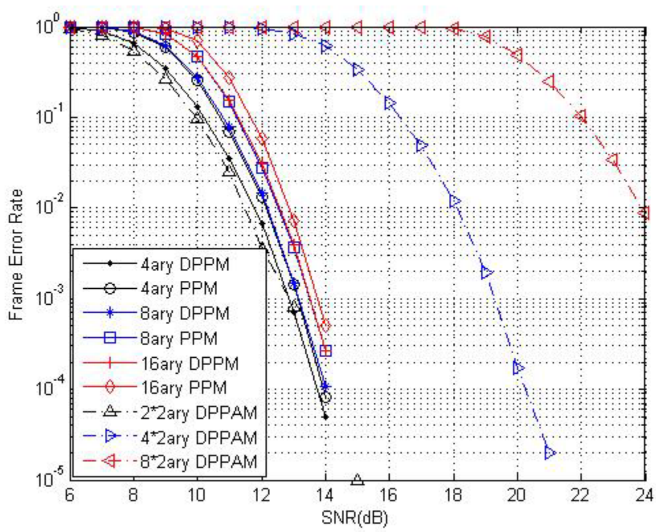

Figure 2: Frame error rate for M×2-ary DPPAM, DPPM and PPM over an AWGN channel with a frame length of 128 bits.

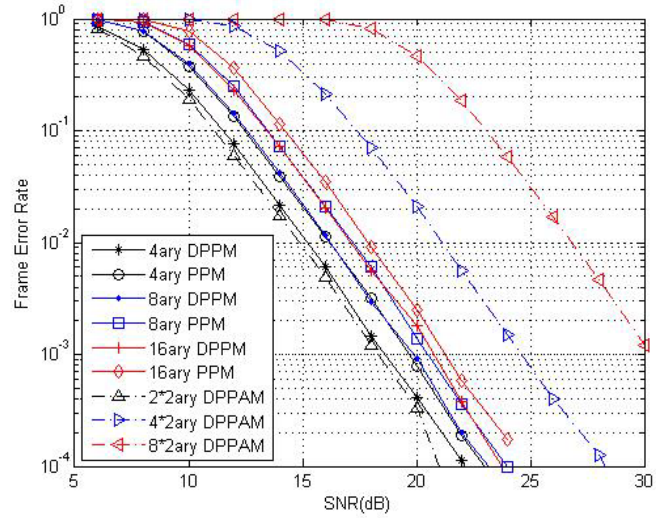

Figure 3: Frame error rate for M×2-ary DPPAM, DPPM and PPM over Nakagami fading channels with a frame length of 128 bits, L=1, and m=3.

REFERENCES

[1] R. A. Scholtz, "Multiple access with time-hopping impulse modulation," in *Proc. IEEE Military Commun. Conf.*, pp. 447–450, Oct. 1993.

[2] F. Ramirez-Mireles and R. A. Scholtz, "System performance analysis of impulse radio modulation," in Proc. *IEEE Radio and Wireless Conf.,* pp. 67–70, Aug. 1998.

[3] H. Zhang and T. A. Gulliver, "Performance and capacity of PAM and PPM UWB time-hopping multiple access communications with receive diversity," *EURASIP J. Applied Signal Proc.*, vol. 2005, pp. 306-315, Mar. 2005.

[4] H. Zhang and T. A. Gulliver, "Capacity of time-hopping PPM and PAM UWB multiple access communications over indoor fading channels," *EURASIP J. Wireless Commun. and Networking*, vol. 2008, Feb. 2008.

[5] H. Zhang, W. Li and T. A. Gulliver, "Pulse position amplitude modulation for time-hopping multiple-access UWB communications," *IEEE Trans. Commun*., vol. 53, no. 8, pp. 1269-1273, Aug. 2005.

[6] B. Wilson Z. F. Ghassemlooy, and E. D. Kaluarachchi, "Digital pulse interval modulation for fiber transmission," *Proc. SPIE*, vol. 2614, pp. 53-59, 1995.

[7] E. D. Kaluarachi, Z. F. Ghassemlooy, and B. Wilson, "Digital pulse interval modulation for transmission over optical fiber with direct detection," *Proc. SPIE*, vol. 2919, pp. 98-105, 1996.

[8] E. D. Kaluarachi, Digital Pulse Interval Modulation for Optical Communication Systems, Ph.D. Thesis, Sheffield Hallam University, U.K., 1997.

[9] A. R. Hayes, Z. Ghassemlooy, and N. L. Seed, "Optical wireless communication using digital pulse interval modulation," *Proc. SPIE*, vol. 3532, pp. 61-69, 1999.

[10] U. Sethakaset and T. A. Gulliver, "Differential amplitude pulse-position modulation for indoor wireless optical communications," *EURASIP J. Wireless Commun. and Networking*, vol. 2005, no. 1, pp. 3-11, 2005.

[11] H. Zhang, T. Udagawa, T. Arita, and M. Nakagawa, "A statistical model for the small-scale multipath fading characteristics of ultra wideband indoor channel," in *Proc. IEEE Conf. on Ultra Wideband Systems and Technologies*, pp. 81-85, May 2002.

[12] D. Cassioli, M. Z. Win, and A. F. Molisch, "The ultra-wide bandwidth indoor channel: From statistical model to simulations," *IEEE J. Select. Areas Commun.,* vol. 20, no. 6, pp. 1247–1257, Aug. 2002.

[13] J. G. Proakis, *Digital Communications*, 4th Ed., McGraw-Hill, New York, 2006.

[14] H. Zhang, T. Lu, J. Wang, and T. A. Gulliver, "Error probability of DPPM UWB systems over Nakagami fading channels with receive diversity," *EURASIP J. Wireless Commun. and Networking*, vol. 2011, Article ID 761369, 9 p., doi:10.1155/2011/761369, Mar. 2011.