Performance of Equicorrelated Ultra-Wideband Pulse-Position-Modulated Signals in the Indoor Wireless Impulse Radio Channel

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Abstract— **Impulse radio (IR) is a spread spectrum (SS) wireless technique in which ultra-wideband (UWB) communication waveforms that consist of trains of time-shifted subnanosecond pulses are modulated to convey information exclusively in the relative time position of the pulses. In this paper we describe the construction of equally correlated (EC) pulse position modulation (PPM) signals, using trains of binary time-shift-keyed UWB subnanosecond pulses. The performance of this EC UWB PPM signals in the indoor IR channel with detection using a Rake receiver is analyzed.**

I. INTRODUCTION

IR [1][2] is a wireless technique potentially viable for short range high speed multiple access (MA) communications over the multipath-impaired indoor channel. In [1] the MA capacity for IR assuming ideal propagation conditions and additive white Gaussian noise (AWGN) was studied. Binary UWB PPM communications signals detected using a correlator receiver were assumed. In order to increase the data transmission rate making efficient use of the signal-to-noise-ratio (SNR) available, it is desirable to use block-coded signals. In this paper we describe the construction of block-coded EC UWB PPM signals. We investigate the performance of this signals in the wireless indoor IR channel perturbed with multipath (MP) and AWGN, with detection performed using both a perfect Rake (PRake) receiver and a selective Rake (SRake) receiver. A PRake receiver is one that has perfect estimators and unlimited number of correlation resources, and the reference signal is able to perfectly match the received signal. A SRake receiver is one where perfect estimators of the K strongest paths are selected to construct a reference signal that is only a mismatched version of the received signal. The underlying question is : What is the degradation in performance when, instead of a PRake receiver, a SRake receiver is used ?

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This paper is organized as follows. In Section II two models for the IR channel are discussed. In section III communications with EC UWB PPM signals in the indoor IR channel with MP with demodulation using a Rake receiver is discussed. In section IV a numerical example is given. The results of the example are discussed in section V.

II. IR CHANNEL MODELS

In this section two models for two types of IR channels are discussed. (1) IR-N: IR channel with ideal propagation conditions and disturbed with AWGN. In the model the transmitted pulse is $\sqrt{E_p}w_{tx}(t) \triangleq \int_{-\infty}^{t} \sqrt{E_p}w(\xi)d\xi$ and the received pulse is $\sqrt{E_p}w(t)+n(t)$. The noise $n(t)$ is AWGN with two-sided power density $\frac{N_o}{2}$. The signal $w(t)$ is the basic monopulse used to convey information. It has duration T_w nanoseconds, two-sided bandwidth W Gigahertz, and energy $E_w \triangleq \int_{-\infty}^{\infty}[w(t)]^2dt = 1$ Joule, hence E_p is the energy in the pulse $\sqrt{E_p}w(t)$. (2) IR-MP: IR channel perturbed with multipath and AWGN. In the model the transmitted pulse is $\sqrt{E_p}w_{tx}(t)$, the received multi-pulse is $\tilde{w}(u,t)+n(t)$, where $\tilde{w}(u,t) \triangleq \sqrt{E_p}w(t) \star h(u,t)$ is the convolution of $\sqrt{E_p}w(t)$

with $h(u,t)$. The $\tilde{w}(u,t)$ is the channel pulse response to $\sqrt{E_p}w_{tx}(t)$. The $h(u,t)$ is the random channel impulse response. The channel is assumed to change slowly with time and to have a MP spread value of T_m, with $T_m >> \frac{1}{W}$. Hence, IR-MP is modeled as a frequency-selective channel [3]. We use an approximate model for $h(u,t)$ where the "subpaths" are clustered in "resolvable" paths, and the delay axis is made discrete by dividing it into T_w ns bins. The delay of any physical path lying in bin k is quantized to $\tau_k = kT_w$ ns. Associated with each τ_k there is an amplitude value $b_k \in \Re$ which is a function of the clustered subpaths lying in bin k. The $\{b_k\}$ will be considered constant during a symbol interval. The resulting approximate model $h_m(u,t)$ for $h(u,t)$ is

$$h(u,t) \approx h_m(u,t) \stackrel{\Delta}{=} \sum_{k=0}^{\infty} b_k(u)\,\delta(t-kT_w),\ b_k(u)\in\Re \quad (1)$$

where $\delta(t)$ is the Dirac delta function, and the u indexes an event taking place in the sample space of a certain random experiment. The random experiment is a measurement experiment performed in an office building where $\tilde{w}(u,t)|_{u=(R,I,J)}$ denotes the IR-MP channel pulse response measured *in the absence of noise* at position (I,J) inside room R. We also define

$$\begin{aligned} h_m^{(K)}(u,t) &\stackrel{\Delta}{=} \sum_{k\in P} b_k(u)\,\delta(t-kT_w) \\ h_{m,c}^{(K)}(u,t) &\stackrel{\Delta}{=} \sum_{k\in P} b_k(u)\,\delta(t-kT_w) \end{aligned} \quad (2)$$

where P is the set of indexes of the K strongest paths in $\tilde{S}_i(u,t)$ and P^c is the set of indexes of all except the K strongest paths in $\tilde{S}_i(u,t)$. It is important to note that the explicit statistical description of $\{b_k(u)\}$ won't be needed for performance evaluation, since sample values taken from experimental measurements will be used.

III. COMMUNICATIONS IN THE IR CHANNEL

In the present analysis we assume one user and perfect synchronization. Under this circumstances, the SS time-hopping sequence modulation has no effect in the correlation properties of the communication signals, and will be omitted in the expressions defining the signals and their correlations values. The signals for the IR-N case, IR-MP PRake case, and IR-MP SRake with K fingers case, will be denoted by $S_i(t)$, $\tilde{S}_i(u,t)$ and $\tilde{S}_i^{(K)}(u,t)$, respectively.

A. UWB PPM REFERENCE SIGNALS

Let $S_i(t)$,$i=1,2,\ldots,M$ be the UWB PPM signal conveying the information. Assume that $\int_{-\infty}^{t} S_i(\xi)d\xi$ is transmitted over the IR channel in the absence of noise. For the IR-N channel, the received signal is $S_i(t)$, and for the IR-MP channel the received signal is $\tilde{S}_i(u,t) = S_i(t) \star h(u,t)$. The reference signals used by the receiver in the demodulation process are [1]

$$\begin{aligned} S_i(t) &\stackrel{\Delta}{=} \sum_{m=0}^{N_s-1} \sqrt{E_p}w(t-mT_f-\delta_i^m), && \text{(IR-N)} \\ \tilde{S}_i(u,t) &\stackrel{\Delta}{=} \sum_{m=0}^{N_s-1} \tilde{w}(u,t-mT_f-\delta_i^m), && \text{(IR-MP PRake)}\ ^2 \\ \tilde{S}_i^{(K)}(u,t) &\stackrel{\Delta}{=} \sum_{m=0}^{N_s-1} \tilde{w}^{(K)}(u,t-mT_f-\delta_i^m), && \text{(IR-MP SRake)} \end{aligned} \quad (3)$$

Here $S_i(t)$ represents the i-th signal in an ensemble of signals, each signal completely identified by the sequence of time shifts $\{\delta_i^m; k = 1,2,\ldots,N_s\}$; [3] $T_f >> T_w$ is the time shift value corresponding to the frame period; and the time shift corresponding to the data modulation is $\delta_i^m \in \{\tau_1 < \tau_2 < \ldots < \tau_N\}$, where $\tau_1 \stackrel{\Delta}{=} 0$ and $0 < \tau_i \le lT_w < T_f$ for $i=2,3,4,\ldots,N$, and l is a positive integer such that $lT_w + T_m + T_w < T_f$ (so the pulses $\tilde{w}^{(K)}(u,t-mT_f-\delta_i^m)$ do not overlap). The ensemble $\{S_i(t)\}$ will be represented by the matrix Δ, where each row corresponds to the time shifts $\{\delta_i^m; m = 1,2,\ldots,N_s\}$ defining the i-th signal. Both ensembles $\{\tilde{S}_i(u,t)\}$ and $\{\tilde{S}_i^{(K)}(u,t)\}$ are still represented by Δ, but now depend on $h(u,t)$ and $h_m^{(K)}(u,t)$, respectively.

For reasons of space, in the following lines we will describe the correlation values $\tilde{R}_{ij}^{(K)}(u)$,$\tilde{\alpha}_{ij}^{(K)}(u)$, $\tilde{R}_{MP}^{(K)}(u,\tau)$, $r_{MP}^{(K)}(u,\tau)$, $\gamma_{MP}^{(K)}(u,\tau)$,$\tilde{C}_{ij}^{(K)}(u)$, $C_{MP}^{(K)}(u,\tau)$ and $c_{MP}^{(K)}(u,\tau)$ only for the IR-MP SRake case. The description for the IR-MP PRake case can be obtained by dropping the index (K) from the expressions and using $h(u,t)$ instead of $h_m^{(K)}(u,t)$. The description for the IR-N case is obtained by

[1] $\tilde{w}(u,t) \stackrel{\Delta}{=} w(t) \star h(u,t)$, and $\tilde{w}^{(K)}(u,t) \stackrel{\Delta}{=} w(t) \star h_m^{(K)}(u,t)$

[3] In IR, N_s is the number of time hops per symbol, and is directly related to the SS processing gain.

suppressing the indexes (K), u and the tilde, by dropping the subindex MP, and using $\delta(t)$ instead of $h^{(K)}(u,t)$.

The correlation between $\tilde{S}_i^{(K)}(u,t)$ and $\tilde{S}_j^{(K)}(u,t)$ is

$$\begin{aligned}\tilde{R}_{ij}^{(K)}(u) &\triangleq \int_{-\infty}^{\infty} \tilde{S}_i^{(K)}(u,t)\tilde{S}_j^{(K)}(u,t)dt \\ &= \sum_{m=0}^{N_s-1}\int_{-\infty}^{\infty} \tilde{w}^{(K)}(u,t-\delta_i^m)\,\tilde{w}^{(K)}(u,t-\delta_j^m)\,dt \quad (4)\end{aligned}$$

Here it is assumed that the impulse response of the channel $h_m^{(k)}(u,t)$ does not change in a time interval of N_sT_f seconds. The correlation function of the signal $\tilde{w}^{(K)}(u,t)$ is

$$\begin{aligned}R_{MP}^{(K)}(u,\tau) &\triangleq \int_{-\infty}^{\infty} \tilde{w}^{(K)}(u,t)\,\tilde{w}^{(K)}(u,t-\tau)\,dt \\ &\triangleq E_p\, r_{MP}^{(K)}(u,\tau), \quad (5)\end{aligned}$$

The normalized signal correlation function is

$$\gamma_{MP}^{(K)}(u,\tau) \triangleq \frac{R_{MP}^{(K)}(u,\tau)}{R_{MP}^{(K)}(u,0)} \quad (6)$$

The energy of $\tilde{w}^{(K)}(u,t)$ is

$$E_{\tilde{w}}^{(K)}(u) \triangleq R_{MP}^{(K)}(u,0) = E_p\, r_{MP}^{(k)}(u,0) \quad (7)$$

where $r_{MP}^{(K)}(u,0)$ is the *"IR-MP channel K-selective multipath power gain"*. [4]

The cross correlation function between $\tilde{w}^{(K)}(u,t)$ and $\tilde{w}_c^{(K)}(u,t)$ is

$$\begin{aligned}C_{MP}^{(K)}(u,\tau) &\triangleq \int_{-\infty}^{\infty} \tilde{w}^{(K)}(u,t)\,\tilde{w}_c^{(K)}(u,t-\tau)\,dt \\ &\triangleq E_p\, c_{MP}^{(K)}(u,\tau), \quad (8)\end{aligned}$$

We can now write $\tilde{R}_{ij}^{(K)}(u)$ in terms of the correlation properties of $\tilde{w}^{(K)}(u,t)$

$$\tilde{R}_{ij}^{(K)}(u) = E_p r_{MP}^{K}(u,0)\sum_{m=0}^{N_s-1}\gamma_{MP}^{(K)}(u,\delta_i^m-\delta_j^m) \quad (9)$$

The energy in the i-th signal is

$$\tilde{E}_S^K(u) = \tilde{R}_{ii}^K(u) = E_s r_{MP}^{(K)}(u,0) \quad (10)$$

where $E_s \triangleq N_sE_p$. The normalized correlation value is

$$\tilde{\alpha}_{ij}^{(K)}(u) \triangleq \frac{\tilde{R}_{ij}^{(K)}(u)}{\tilde{R}_{ii}^{(K)}(u)} = \frac{1}{N_s}\sum_{m=0}^{N_s-1}\gamma_{MP}^{(K)}(u,\delta_i^m-\delta_j^m) \quad (11)$$

[4] "IR-MP channel multipath power gain" in the PRake case; and "IR-N channel power gain" in the IR-N case.

with $\tilde{\alpha}_{ii}^{(K)}(u)=1$. The cross correlation between $\tilde{S}_i^{(K)}(u,t)$ and $\tilde{S}_{j,c}^{(K)}(u,t)$ is

$$\begin{aligned}\tilde{C}_{ij}^{(K)}(u) &\triangleq \int_{-\infty}^{\infty} \tilde{S}_i^{(K)}(u,t)\tilde{S}_{j,c}^{(K)}(u,t)dt \\ &= \sum_{m=0}^{N_s-1}\int_{-\infty}^{\infty} \tilde{w}^{(K)}(u,t-\delta_i^m)\,\tilde{w}_c^{(K)}(u,t-\delta_j^m)\,dt \\ &\triangleq E_p\sum_{m=0}^{N_s-1} c_{MP}^{(K)}(u,\delta_i^m-\delta_j^k) \quad (12)\end{aligned}$$

with $\tilde{C}_{ii}^{(K)}(u)=0$, since $h_m^{(K)}(u,t)$ and $h_{m,c}^{(K)}(u,t)$ do not overlap.

B. EQUALLY CORRELATED UWB PPM SIGNALS

One method to generate equally correlated $\{S_i(t)\}$ with $M \le N_s$ and N_s odd is by deleting the first column of a Hadamard matrix and using the rows of this matrix and mapping $+1 \to \tau_1$ and $-1 \to \tau_2$. The resulting normalized correlation value is [5]

$$\begin{aligned}C &= \tfrac{N_s-1}{2N_s}\gamma(0)+\tfrac{N_s+1}{2N_s}\gamma(\tau_1-\tau_2) \\ &\approx \tfrac{1+\gamma(\tau_1-\tau_2)}{2} \text{ for } N_s>>1 \quad (13)\end{aligned}$$

The normalized correlation between $\tilde{S}_i^{(K)}(u,t)$ and $\tilde{S}_j^{(K)}(u,t)$ is

$$\tilde{C}^{(K)}(u) \approx \tfrac{1+\gamma_{MP}^{(K)}(u,\tau_1-\tau_2)}{2} \text{ for } N_s>>1 \quad (14)$$

and the unnormalized cross correlation between $\tilde{S}_i^{(K)}(u,t)$ and $\tilde{S}_{j,c}^{(K)}(u,t)$ is

$$\begin{aligned}\tilde{C}_c^K(u) &= \tfrac{N_s-1}{2}E_pc_{MP}^{(K)}(u,0)+\tfrac{N_s+1}{2}E_pc_{MP}^{(K)}(u,\tau_1-\tau_2) \\ &\approx \tfrac{E_sc_{MP}^{(K)}(u,\tau_1-\tau_2)}{2} \text{ for } N_s>>1 \quad (15)\end{aligned}$$

C. DEMODULATION USING A *Rake* RECEIVER

Consider the transmission of information over the IR-MP channel using UWB PPM signals. When the signal $\int_{-\infty}^{t} S_j(\xi)d\xi, j=1,2,\ldots,M$ is transmitted, the received signal in a symbol interval $T \triangleq N_sT_f$ can be written [6]

$$\begin{aligned}r(u_o,t) &= \tilde{S}_j(u_o,t)+n(t),\ 0\le t\le T \\ &= \tilde{S}_j^{(K)}(u_o,t)+\tilde{S}_{j,c}^{(K)}(u_o,t)+n(t) \\ &= \tilde{S}_j^{(K)}(u_o,t)+n_{tot}(t) \quad (16)\end{aligned}$$

[5] $\gamma(\tau) \triangleq \int_{-\infty}^{\infty} w(t)w(t-\tau)dt$

[6] For both IR-MP PRake case and IR-N case $\tilde{S}_{j,c}^{(K)}(u_o,t)=0$.

where

$$n_{tot}(t) \triangleq \tilde{S}_{j,c}^{(K)}(u_o,t) + n(t) \qquad (17)$$

The term $\tilde{S}_{j,c}^{(K)}(u_o,t)$ can be considered as a signal dependent self-noise, that is statistically independent of n(t) and which ultimately limits the performance. An approximate analysis to the performance of the SRake receiver can be obtained by treating the self-noise as an additive Gaussian with mean zero and power equal to its variance.

Conditioned on the random event $u = u_o$, the impulse response of the channel is time-invariant and deterministic. [7]. In this case the received signal is $r(u_o,t)$ and the conditioned decision variables for coherent detection of the M-ary UWB PPM signals can be expressed as

$$\tilde{y}_{i|j}(u_o) = \int_0^T r(u_o,t)\tilde{S}_i^{(K)}(u_o,t)dt, \; i=1,2,\ldots,M \qquad (18)$$

It can be shown that $\{\tilde{y}_{i|j}(u_o)\}$ are Gaussian and correlated. Hence the demodulation problem becomes the coherent detection of M equal-energy signals in the presence of signal dependent self-noise in addition to AWGN.

D. PERFORMANCE USING a Rake RECEIVER

Conditioned on $u = u_o$, both the probability of error PE and the union bound on PE are functions of the SNR and the correlation values of section III-B [4][5]. The union bound on the bit PE for equicorrelated UWB PPM signals can be written

$$\begin{aligned}
UBP_b &= \tfrac{M}{4}\mathrm{Erfc}\left(\tfrac{1}{\sqrt{2}}\tfrac{m_y}{\sigma_y}\right) && \text{(IR-N)}\\
UB\tilde{P}_b(u_o) &= \tfrac{M}{4}\mathrm{Erfc}\left(\tfrac{1}{\sqrt{2}}\tfrac{m_{\tilde{y}}(u_o)}{\sigma_{\tilde{y}}(u_o)}\right) && \text{(PRake)}\\
UB\tilde{P}_b^{(k)}(u_o) &= \tfrac{M}{4}\mathrm{Erfc}\left(\tfrac{1}{\sqrt{2}}\left[\left(\tfrac{m_{\hat{y}}^K(u_o)}{\sigma_{\hat{y}}^K(u_o)}\right)^{-2} + \right.\right.\\
&\qquad \left.\left.\left(\tfrac{m_{\hat{y}}^K(u_o)}{\sigma_c^K(u_o)}\right)^{-2}\right]^{-\frac{1}{2}}\right) && \text{(SRake)}
\end{aligned} \qquad (19)$$

where

$$\begin{aligned}
\left(\tfrac{m_y}{\sigma_y}\right) &= \sqrt{\tfrac{E_b}{N_o}\log_2(M)(1-C)},\\
\left(\tfrac{m_{\tilde{y}}(u_o)}{\sigma_y(u_o)}\right) &= \sqrt{\tfrac{E_b r_{MP}(u_o,0)}{N_o}\log_2(M)(1-\tilde{C}(u_o))},
\end{aligned}$$

[7]From a Rake receiver perspective, the underlying assumptions are that the receiver can estimate $\{b_k(u)\}$ perfectly and that within any one signaling interval of length T the tap weights are treated as constants.

$$\begin{aligned}
m_{\hat{y}}^K(u_o) &= E_b\log_2(M)r_{MP}^{(K)}(u_o,0)[1-\tilde{C}^K(u_o)],\\
\left(\sigma_{\hat{y}}^K(u_o)\right)^2 &= N_oE_b\log_2(M)r_{MP}^{(K)}(u_o,0)[1-\tilde{C}^K(u_o)],\\
\left(\sigma_c^K\right)^2 &= \left(\tilde{C}_c^K(u_o)\right)^2
\end{aligned} \qquad (20)$$

The values in (19) and (20) are conditioned on the event $u = u_o = (R_o, I_o, J_o)$, and depends on $\tilde{w}(u,t)|_{u=(Ro,Io,Jo)}$, the channel pulse response measured in the absence of noise at position (Io, Jo) inside room Ro. The $r_{MP}(u_o,0)$ and $r_{MP}^{(K)}(u_o,0)$ values accounts for variations in the received signal energy due to fading caused by multipath. The $\tilde{C}(u_o)$ and $\tilde{C}^{(K)}(u_o)$ values accounts for distortions in the signal correlation function caused by multipath [6].

Taking the expected value $\mathbf{E}_u\{\cdot\}$ with respect to u over all measurements and over all the rooms

$$\begin{aligned}
\overline{UBP}_b\left(\tfrac{\overline{E}_b}{N_o}\right) &= \mathbf{E}_u\{UB\tilde{P}_b(u)\}\\
\overline{UBP}_b^{(K)}\left(\tfrac{\overline{E}_b^K}{N_o}\right) &= \mathbf{E}_u\{UB\tilde{P}_b^{(K)}(u)\}
\end{aligned} \qquad (21)$$

where

$$\begin{aligned}
\left(\tfrac{\overline{E}_b}{N_o}\right) &\triangleq \mathbf{E}_u\left\{\left(\tfrac{m_{\tilde{y}}}{\sigma_{\tilde{y}}}\right)\right\}\\
\left(\tfrac{\overline{E}_b^K}{N_o}\right) &\triangleq \mathbf{E}_u\left\{\left(\tfrac{m_{\hat{y}}^K(u_o)}{\sigma_{tot}^K(u_o)}\right)\right\}
\end{aligned} \qquad (22)$$

is the average received symbol SNR. The expected values in (21) can be approximated by the sample mean values

$$\begin{aligned}
\overline{UBP}_b\left(\tfrac{\overline{E}_b^K}{N_o}\right) &\approx \tfrac{1}{U_o^*}\textstyle\sum_{u_o=1}^{U_o^*} UB\tilde{P}_b(u_o)\\
\overline{UBP}_b^{(K)}\left(\tfrac{\overline{E}_b^K}{N_o}\right) &\approx \tfrac{1}{U_o^*}\textstyle\sum_{u_o=1}^{U_o^*} UB\tilde{P}_b^{(K)}(u_o)
\end{aligned} \qquad (23)$$

IV. NUMERICAL EXAMPLE

Figures (1) and (2) shows the curves for $\overline{UBP}_b\left(\frac{\overline{E}_b}{N_o}\right)$ and $\overline{UBP}_b^{(K)}\left(\frac{\overline{E}_b^K}{N_o}\right)$, $K = 1, 2, 4, 8, 16, 32, 64$, $M = 2, 4, 8, 16, 32$, using the specific pulse waveform

$$w(t) = \left[1-4\pi\left[\tfrac{t}{t_n}\right]^2\right]\exp\left(-2\pi\left[\tfrac{t}{t_n}\right]^2\right) \qquad (24)$$

The value $t_n = 0.7531ns$ was used to fit the model $w(t)$ to the measured waveform $w_T(t)$. The UWB pulse $w_T(t)$ is a unitary-energy template with duration $T_w = 1.5 \; ns$

that was taken from a multipath-free and noise-free measurement. The signal correlation function of $w(t)$ is

$$\gamma_w(t) = \left[1-4\pi\left[\tfrac{t}{\tau_n}\right]^2+\tfrac{4\pi^2}{3}\left[\tfrac{t}{\tau_n}\right]^4\right]\times \exp\left(-2\pi\left[\tfrac{t}{\tau_n}\right]^2\right) \quad (25)$$

which has a minimum $\gamma_{min} = -0.6183$ at the time shift value $\tau_{min} = 0.7531 \quad ns$.

The channel pulse responses $\tilde{w}(u_o,t), u_o = 1,2,\ldots,U_o^* = 392$ come from signal propagation data recorded in an ultra-wide-band measurements experiment [7]. The pulse $\tilde{w}^{(K)}(u_o,t)$ is calculated as follows

$$\begin{aligned} \tilde{w}^{(K)}(u_o,t) &\triangleq \textstyle\sum_{k\in P} b_k(u_o) w_T(t-kT_w) \\ |b_k(u_o)| &\triangleq \sqrt{\int_{(k-1)T_w}^{kT_w} \tilde{w}^2(u_o,t)dt} \\ \text{sign}(b_k(u_o)) &\triangleq \begin{cases} +1 & \text{if } \max_t(\tilde{w}(u_o,t)) > \min_t(\tilde{w}(u_o,t)), \\ & t\in[(k-1)T_w,kT_w], \\ -1 & \text{otherwise} \end{cases} \end{aligned} \quad (26)$$

For the time shift we use $\tau_1 = 0$ and $\tau_2 = \tau_{min}$, hence $\gamma(\tau_1 - \tau_2) = \gamma_{min}$.

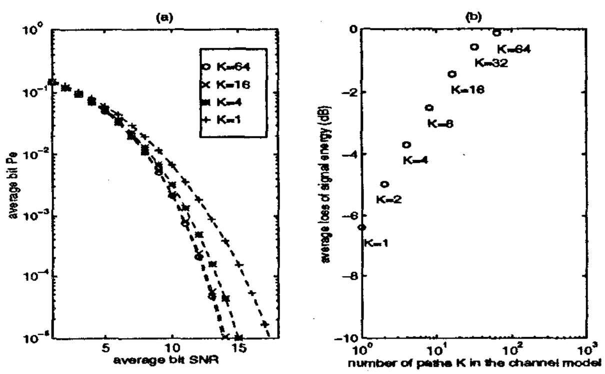

Fig. 1. (a)The $\overline{UBP}_b^{(K)}\left(\frac{\overline{E}_b^K}{N_o}\right)$ for $K = 1,4,16,64$ paths and $M = 2$ signals. (b)Average loss in the energy of $\tilde{S}_i^{(K)}(u,t)$ with respect to the energy in $\tilde{S}_i(u,t)$ for $K = 1,2,4,8,16,32,64$ paths.

V. DISCUSSION OF RESULTS

Figure (2) compares the performance of M-ary EC UWB PPM signals in the IR-MP channel for $M = 2,4,8,16,32$ signals. The results for the PRake receiver are based on the actual measured signals. The results for the all-paths SRake receiver are based on $h_m^{(k)}(u,t)$ with the parameters of the model derived from the actual measured signal. There is a fair agreement between both results, which endorses the calculations for the K-paths SRake receiver shown in figure (1). [8] The $\overline{UBP}_b^{(K)}\left(\frac{\overline{E}_b^K}{N_o}\right)$ curves in figure (1a) suggest that we can get a fair performance using a relatively simple SRake receiver with a modest number of fingers. Figure (1b) suggest the presence of a strong specular component, with a good portion of the total signal energy contained in a few paths. Future work can be done to try to find a good signal design that maximize both the energy captured and the probability of detection. Two weakness in this analysis are that the clustering of subpaths in $\tilde{w}^{(K)}(u_o,t)$ is not unique, and that we do not have a measure of the confidence interval for the calculation in (23).

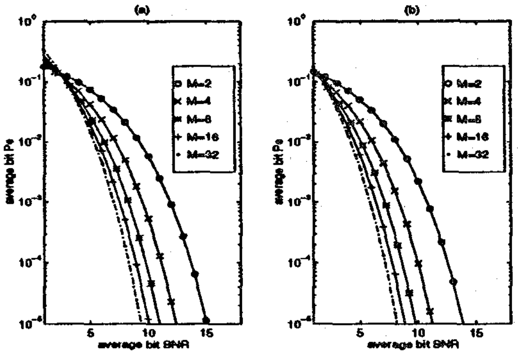

Fig. 2. Curves for $M = 2,4,8,16,32$ signals. (a)The $\overline{UBP}_b\left(\frac{\overline{E}_b}{N_o}\right)$, and (b)The $\overline{UBP}_b^{(K)}\left(\frac{\overline{E}_b^K}{N_o}\right)$ when $\tilde{S}_i^{(K)}(u,t)$ includes all paths in the model.

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[8] The $M = 4,8,16,32$ curves for the K-paths SRake receiver can be obtained from the $M = 2$ curves.