Performance of Ultra-Wideband Time-Shift-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 sub-nanosecond pulses are modulated to convey information exclusively in the relative time position of the pulses. In this paper we make an assessment of the performance of non-binary IR modulation in the presence of multipath with detection using a Rake receiver.**

I. INTRODUCTION

Reliable simultaneous communications among multiple users exchanging information at rates on the order of Megabits per second over the indoor wireless channel is a technical challenge. This channel is impaired by deep multipath nulls (fading) produced by dense multiple path signals arriving at the receiver with different time delays that can be as small as fractions of nanoseconds [1]. For the signals to survive these nulls, it is necessary to increase the transmitted power significantly and/or use diversity techniques [2]. Frequency diversity can be achieved using communication signals with bandwidths on the order of GigaHertz to allow a Rake receiver [3] to be operable in this dense multipath environment.

One convenient way to generate this UWB communication signals is to use subnanosecond pulses. The technology for receiving and generating such pulses and controlling their relative position in the time axis with great accuracy is now available [4]. With this technology it is possible to build UWB communication waveforms that consist of trains of time-shifted subnanosecond pulses that can be received by correlation detection virtually at the antenna terminals, making a relatively simple and low-cost receiver possible [5][6]. In [5] the single-user multiple-access performance of IR assuming ideal propagation conditions and additive white Gaussian noise (AWGN) was studied. Binary time-shift-keyed modulated signals detected using a correlation receiver were used. The use of non-binary IR modulation is attractive, since it allows to increase the data transmission rate without increasing the transmission bandwidth. In this paper we make a prompt assessment of the performance of non-binary IR modulation in the presence of multipath (no multiple access interference is considered here). Previous work in [7] only considered degradation in the signal correlation function caused by multipath. In this work we take into account both fading and signal correlation distortion. We compute the performance using an infinite Rake receiver and calculated degradation in performance using a selective Rake receiver. An infinite Rake (IRake) receiver is one that has an unlimited number of correlation resources and is able to perfectly match the signal received over the wireless IR channel impaired with multipath. A selective Rake (SRake) receiver is one where a limited number of paths or "fingers" are used to construct a reference signal that is only a mismatched version of the signal received over the wireless IR channel impaired with multipath.

This paper is organized as follows. In Section II two models for the IR channel are discussed. In section III multiple time-shift-keyed (M-TSK) signals are described. In section IV demodulation of M-TSK signals transmitted over the wireless indoor IR channel perturbed with multipath using a Rake receiver is described. In section V a numerical example is given. In section VI the results are discussed.

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II. IR CHANNEL MODELS

In this section two models for two types of IR channels are discussed. (1) IR-N: Wireless IR channel with free space propagation conditions and disturbed with AWGN. In this channel model the transmitted signal is $\sqrt{E_s}w_{tx}(t) \triangleq \int_{-\infty}^{t} \sqrt{E_s}w(\xi)d\xi$ and the received signal is $\sqrt{E_s}w(t)+n(t)$, where $n(t)$ is AWGN with two-sided power density $\frac{N_o}{2}$, and $w(t)$ is a pulse with two-sided bandwidth W. (2) IR-MP: Wireless indoor IR channel perturbed with multipath and AWGN. In this channel model the transmitted signal is $\sqrt{E_s}w_{tx}(t)$, the received signal is $\tilde{w}(u,t)+n(t)$, where $\tilde{w}(u,t) \triangleq \sqrt{E_s}w(t)\star h(u,t)$ is the convolution of $\sqrt{E_s}w(t)$ with $h(u,t)$. The $\tilde{w}(u,t)$ is the channel response to the pulse $\sqrt{E_s}w_{tx}(t)$. The $h(u,t)$ is the random channel impulse response which is assumed to have the form of a tapped delay line with tap spacing $\{\tau_k(u)\}$ and tap weight coefficients $\{a_k(u)\}$ and is given by

$$h(u,t) \triangleq \sum_{k=1}^{\infty} a_k(u)\,\delta(t-\tau_k(u)),\; a_k(u) \in \Re \qquad (1)$$

where $\delta(t)$ is the Dirac delta function. The channel is assumed to change slowly with time and to have a multipath spread value of T_m, with $T_m >> \frac{1}{W}$. Hence, IR-MP is modeled as a frequency-selective channel [8]. 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. For an elaborated characterization of this channel see the work in [9].

III. M-TSK SIGNALS

A. M-TSK SIGNALS IN FREE SPACE PROPAGATION CONDITIONS

The signal $w(t)$ is the basic monopulse used to transmit 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. The M-TSK signal set

$$\{\sqrt{E_s}w(t-\tau_1), \sqrt{E_s}w(t-\tau_2), \ldots, \sqrt{E_s}w(t-\tau_M)\} \qquad (2)$$

with $\tau_1=0, \tau_1<\tau_2\leq T_w, \ldots, \tau_{M-1}<\tau_M\leq(M-1)T_w$ form an M-ary set of coherent time-shift-keyed signals. The $\sqrt{E_s}w(t-\tau_i)$ is the signal received in the absence of noise when $\sqrt{E_s}w_{tx}(t-\tau_i)$ is transmitted over the IR-N channel. The signal correlation function of $\sqrt{E_s}w(t)$ is defined by

$$R_w(\tau) \triangleq E_s \int_{-\infty}^{\infty} w(t)w(t-\tau)dt, \qquad (3)$$

and the normalized signal correlation function is defined by

$$\gamma_w(\tau) \triangleq \frac{R_w(\tau)}{R_w(0)} \qquad (4)$$

Since $E_w = 1$, $E_s \triangleq R_w(0)$ is the energy of $\sqrt{E_s}w(t)$. The minimum value of $\gamma_w(\tau)$ will be denoted γ_{min}, and τ_{min} will denote the smallest value of τ in $[0,T_w]$ such that $\gamma_{min} = \gamma_w(\tau_{min})$. The normalized correlation value between $\sqrt{E_s}w(t-\tau_i)$ and $\sqrt{E_s}w(t-\tau_j)$ is given by $\alpha_{ij} \triangleq \gamma_w(\tau_i-\tau_j)$.

B. EFFECT OF MULTIPATH IN M-TSK SIGNALS

Assume the signal $\sqrt{E_s}w_{tx}(t-\tau_j)$ is transmitted over the IR-MP channel. The received signal in the absence of noise is $\tilde{w}(u,t-\tau_j) \triangleq \sqrt{E_s}w(t-\tau_j)\star h(u,t)$. The signal correlation function of $\tilde{w}(u,t)$ is defined by

$$\begin{aligned} R_{MP}(u,\tau) &\triangleq \int_{-\infty}^{\infty} \tilde{w}(u,t)\,\tilde{w}(u,t-\tau)\,dt \\ &= E_s\, r_{MP}(u,\tau) \qquad (5) \\ r_{MP}(u,\tau) &\triangleq \int_{-\infty}^{\infty} [w(t)\star h(u,t)][w(t-\tau)\star h(u,t)]\,dt \qquad (6) \end{aligned}$$

The normalized signal correlation function is

$$\gamma_{MP}(u,\tau) \triangleq \frac{R_{MP}(u,\tau)}{R_{MP}(u,0)} \qquad (7)$$

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

$$E_{\tilde{w}}(u) \triangleq R_{MP}(u,0) = E_s\, r_{MP}(u,0) \qquad (8)$$

where $r_{MP}(u,0)$ is the *"IR-MP channel total multipath power gain"*. The normalized correlation value between $\tilde{w}(u,t-\tau_i)$ and $\tilde{w}(u,t-\tau_j)$ is given by $\tilde{\alpha}_{ij}(u) \triangleq \gamma_{MP}(u,\tau_i-\tau_j)$.

C. MISMATCHED REFERENCE SIGNALS

The received signal $\tilde{w}(u,t-\tau_j)$ can be "decomposed" in two parts

$$\tilde{w}(u,t-\tau_j) = \tilde{w}^{(K)}(u,t-\tau_j) + \tilde{w}_c^{(K)}(u,t-\tau_i) \qquad (9)$$

$$\tilde{w}^{(K)}(u,t-\tau_j) \triangleq \sqrt{E_s} w(t-\tau_j)\star\sum_{k\in P} a_k(u)\,\delta(t-\tau_k(u)) \quad (10)$$

$$\tilde{w}_c^{(K)}(u,t-\tau_j) \triangleq \sqrt{E_s} w(t-\tau_j)\star\sum_{k\in P^c} a_k(u)\,\delta(t-\tau_k(u)) \quad (11)$$

where P is the set of indices of the K strongest signal paths of $\tilde{w}(u,t-\tau_j)$ and P^c is the set of indices of all except the K strongest signal paths of $\tilde{w}(u,t-\tau_j)$. The $\tilde{w}^{(K)}(u,t-\tau_j)$ is a mismatched reference signal in a SRake receiver, and $\tilde{w}_c^{(K)}(u,t-\tau_j)$ is the "complement" to $\tilde{w}^{(K)}(u,t-\tau_j)$. The correlation function of the SRake reference signal $\tilde{w}^{(K)}(u,t)$ is

$$R_{MP}^{(K)}(u,\tau) \triangleq \int_{-\infty}^{\infty} \tilde{w}^{(K)}(u,t)\,\tilde{w}^{(K)}(u,t-\tau)\,dt = E_s\, r_{MP}^{(K)}(u,\tau) \quad (12)$$

$$r_{MP}^{(K)}(u,\tau) \triangleq \int_{-\infty}^{\infty}\left[w(t)\star\sum_{k\in P} a_k(u)\,\delta(t-\tau_k(u))\right]\times \left[w(t-\tau)\star\sum_{l\in P} a_l(u)\,\delta(t-\tau_l(u))\right] dt \quad (13)$$

The normalized signal correlation function is defined by

$$\gamma_{MP}^{(K)}(u,\tau) \triangleq \frac{R_{MP}^{(K)}(u,\tau)}{R_{MP}^{(K)}(u,0)} \quad (14)$$

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

$$E_{\tilde{w}}^{(K)}(u) \triangleq R_{MP}^{(K)}(u,0) = E_s\, r_{MP}^{(k)}(u,0) \quad (15)$$

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

The normalized correlation value between $\tilde{w}^{(K)}(u,t-\tau_i)$ and $\tilde{w}^{(K)}(u,t-\tau_j)$ is given by $\tilde{\alpha}_{ij}^{(K)}(u) \triangleq \gamma_{MP}^{(K)}(u,\tau_i-\tau_j)$. The signal cross correlation function between $\tilde{w}^{(K)}(u,t)$ and $\tilde{w}_c^{(K)}(u,t)$ is defined by

$$C_{MP}^{(K)}(u,\tau) \triangleq \int_{-\infty}^{\infty} \tilde{w}^{(K)}(u,t)\,\tilde{w}_c^{(K)}(u,t-\tau)\,dt = E_s\, c_{MP}^{(K)}(u,\tau) \quad (16)$$

$$c_{MP}^{(K)}(u,\tau) \triangleq \int_{-\infty}^{\infty}\left[w(t)\star\sum_{k\in P} a_k(u)\,\delta(t-\tau_k(u))\right]\times \left[w(t-\tau)\star\sum_{l\in P^c} a_l(u)\,\delta(t-\tau_l(u))\right] dt \quad (17)$$

IV. DEMODULATION USING A Rake RECEIVER

Consider the transmission of information over the IR-MP channel using M-TSK signals. When the signal $\sqrt{E_s} w_{tx}(t-\tau_j)$, $j=1,2,\ldots,M$ is transmitted, the received signal becomes $r(u,t)=\tilde{w}(u,t-\tau_j)+n(t)$, $0\le t\le T$, $T\triangleq\tau_M+T_m$. Conditioned on the random event $u=u_o$, $h(u_o,t)$ represents the impulse response of a time-invariant deterministic channel In this case the received signal is $r(u_o,t)$ and the detection problem becomes the coherent detection of M equal-energy signals in AWGN, and the optimum receiver consist of M filters matched to the M signals $\{\tilde{w}(u_o,t-\tau_1),\tilde{w}(u_o,t-\tau_2),\ldots,\tilde{w}(u_o,t-\tau_M)\}$ followed by samplers and a decision circuit that selects the signal corresponding to the largest output [10].

A. PERFORMANCE OF THE IRake RECEIVER

The performance of the IRake receiver will be now discussed, under the assumption that the receiver is able to perfectly match the signal received over the IR-MP channel. For simplicity in the analysis, we will work with the union bound on the symbol error probability

$$UBP_e(u_o) = \frac{1}{M}\sum_{\substack{i=1\\ i\neq j}}^{M}\sum_{j=1}^{M} Q\left(\sqrt{\frac{m_{\tilde{y}}^2(i|j)}{\sigma_{\tilde{y}}^2(i,j)}}\right) \quad (18)$$

where $\left(\frac{m_{\tilde{y}}^2(i|j)}{\sigma_{\tilde{y}}^2(i,j)}\right)$ is the SNR value involved in the decision between the pair of signals (i,j), and $m_{\tilde{y}}(i|j)$ and $\sigma_{\tilde{y}}^2(i,j)$ are the mean and variance of the decision variables $\tilde{y}_{i|j}$, respectively, and are given by

$$m_{\tilde{y}}(i|j) = E_s r_{MP}(u_o,0)\,[1-\tilde{\alpha}_{i,j}(u_o)] \quad (19)$$

$$\sigma_{\tilde{y}}^2(i,j) = N_o E_s r_{MP}(u_o,0)\,[1-\tilde{\alpha}_{i,j}(u_o)] \quad (20)$$

Hence,

$$\left(\frac{m_{\tilde{y}}^2(i|j)}{\sigma_{\tilde{y}}^2(i,j)}\right) = \frac{E_s r_{MP}(u_o,0)}{N_o}[1-\tilde{\alpha}_{ij}(u_o)] \quad (21)$$

The expression in (18) is conditioned on the event $u=u_o=(R_o,I_o,J_o)$, and depends on $R_{MP}(u_o,\tau)$, which is the signal correlation function of $\tilde{w}(u,t)|_{u=(Ro,Io,Jo)}$. Taking the expected value $E_u\{\cdot\}$ with respect to u over all measurements and over all the rooms in (18) we get

$$\overline{UBP}_e\left(\frac{E_a}{N_o}\right) = E_u\{UBP_e(u)\} \quad (22)$$

where $\left(\frac{E_a}{N_o}\right)\triangleq\left(\frac{E_s}{N_o}\right)E_u\{r_{MP}(u,0)\}$ is the average received symbol SNR.

B. PERFORMANCE OF THE SRake RECEIVER

The performance of the SRake receiver will be now discussed, under the conditions that the receiver is able to construct a partial (or mismatched) reference signal $\tilde{w}^{(K)}(u_o, t-\tau_i)_{,i=1,2,\ldots,M}$ based on the K strongest paths of the signal $\tilde{w}(u_o, t-\tau_i)_{,i=1,2,\ldots,M}$. Assuming that the signal $\sqrt{E_s} w_{tx}(t-\tau_j)$ was transmitted, the received signal can be written

$$r(u_o, t) = \tilde{w}^{(K)}(u_o, t-\tau_j) + n_{tot}(t) \quad (23)$$

$$n_{tot}(t) \triangleq \tilde{w}_c^{(K)}(u_o, t-\tau_j) + n(t) \quad (24)$$

The term $\tilde{w}_c^{(K)}(u_o, t-\tau_j)$ can be considered a signal dependent self-noise, that is statistically independent of $n(t)$ and that imposes a limit in the performance of the SRake receiver. An approximate performance analysis can be obtained by treating the self-noise as an additive Gaussian with mean zero and power equal to its variance. In this case the union bound on the symbol error probability is found to be

$$UBP_e^{(K)}(u_o) = \frac{1}{M}\sum_{j=1}^{M}\sum_{\substack{i=1 \\ i\neq j}}^{M} Q\left(\sqrt{\frac{m_{\hat{y}}^2(i|j)}{\sigma_{tot}^2(i,j)}}\right) \quad (25)$$

where $\left(\frac{m_{\hat{y}}^2(i|j)}{\sigma_{tot}^2(i,j)}\right)$ is the SNR value involved in the decision between the pair of signals (i,j), and $m_{\hat{y}}(i|j)$ and $\sigma_{total}^2(i,j)$ are the mean and variance of the decision variables $\hat{y}_{i|j}$, respectively, and are given by

$$m_{\hat{y}}(i|j) = E_s r_{MP}^{(K)}(u_o, 0)\left[1-\tilde{\alpha}_{i,j}^{(K)}(u_o)\right] \quad (26)$$

$$\sigma_{tot}^2(i,j) = \sigma_{\hat{y}}^2(i,j) + \sigma_c^2(i,j) \quad (27)$$

where

$$\sigma_{\hat{y}}^2(i,j) \triangleq N_o E_s r_{MP}^{(K)}(u_o,0)\left[1-\tilde{\alpha}_{i,j}^{(K)}(u_o)\right] \quad (28)$$

$$\sigma_c^2(i,j) \triangleq (E_s)^2\left[c_{MP}^{(K)}(u_o,0)-c_{MP}^{(K)}(u_o,\tau_j-\tau_i)\right]^2 \quad (29)$$

The $\sigma_{\hat{y}}^2(i,j)$ is the term that accounts for the presence of the AWGN, and the $\sigma_c^2(i,j)$ is the term that accounts for the presence of the signal-dependent self-noise. Hence

$$\left(\frac{m_{\hat{y}}^2(i|j)}{\sigma_{tot}^2(i,j)}\right) = \left[\left(\frac{m_{\hat{y}}^2(i|j)}{\sigma_{\hat{y}}^2(i,j)}\right)^{-1} + \left(\frac{m_{\hat{y}}^2(i|j)}{\sigma_c^2(i,j)}\right)^{-1}\right]^{-1} \quad (30)$$

Taking the expected value $E_u\{\cdot\}$ with respect to u over all measurements and over all the rooms in (25) we get

$$\overline{UBP}_e^{(K)}\left(\frac{E_a^K}{N_o}\right) = E_u\{UBP_e(u)\} \quad (31)$$

where $\left(\frac{E_a^K}{N_o}\right) \triangleq \left(\frac{E_s}{N_o}\right) E_u\left\{\frac{m_{\hat{y}}^2(i|j)}{\sigma_{tot}^2(i,j)}\right\}$ is the average received symbol SNR.

V. NUMERICAL EXAMPLE

In this section, the calculation in (22) and (31) with $K = 2, 5, 10$ is done for two M-TSK signal sets ($M = 4$) defined by the time shifts [1]

$$\begin{array}{ll} (a) & (\tau_1=0,\ \tau_2=\tau_{min},\ \tau_3=T_w+\tau_{min},\ \tau_4=T_w+2\tau_{min}) \\ (b) & (\tau_1=0,\ \tau_2=Tw,\ \tau_3=2T_w,\ \tau_4=3T_w) \end{array} \quad (32)$$

In IR modulation, the UWB received pulse $w(t)$ can be modeled by

$$w(t) = \left[1-4\pi\left[\tfrac{t}{t_n}\right]^2\right]\exp\left(-2\pi\left[\tfrac{t}{t_n}\right]^2\right) \quad (33)$$

where the value $t_n = 0.7531\ ns$ 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 corresponding to $w(t)$ is

$$\gamma_w(t) = \left[1-4\pi\left[\tfrac{t}{t_n}\right]^2+\tfrac{4\pi^2}{3}\left[\tfrac{t}{t_n}\right]^4\right]\exp\left(-2\pi\left[\tfrac{t}{t_n}\right]^2\right) \quad (34)$$

which has a minimum $\gamma_{min} = -0.6183$ at the time shift value $\tau_{min} = 0.408ns$.

The pulse responses $\tilde{w}(u,t)$ come from signal propagation data recorded in an ultra-wide-band measurements experiment [11]. In this experiment, multipath profiles are measured in different rooms and hallways. In each room, $T_m = 300$ nanosecond-long windows of multipath measurements are recorded at 49 different locations arranged spatially in a 7x7 square grid with 6 inch spacing, with the transmitter, the receiver and the environment kept stationary. Three hundred and fifty two normalized correlation functions $\gamma_{MP}(u_o,\tau)$ were calculated from measured signals received in eight different rooms. Due to the multipath effects, the signal correlations at each point are different from each other. They are the sample functions of $\gamma_{MP}(u,\tau)$ as described before.

Figure 1 shows $\overline{UBP}_e\left(\frac{E_a}{N_o}\right)$ and $\overline{UBP}_e^{(K)}\left(\frac{E_a^K}{N_o}\right)$ for $K = 2, 5, 10$. The curves in figure 1 (a) and figure 1 (b) represent the performance of the M-TSK signal sets (a) and (b) respectively, in the IR-MP channel when an IRake receiver and a SRake receiver with $K = 2, 5, 10$ fingers are

[1] In [7], the M-TSK set in (a) was shown to have the best performance among four different sets studied, including set (b).

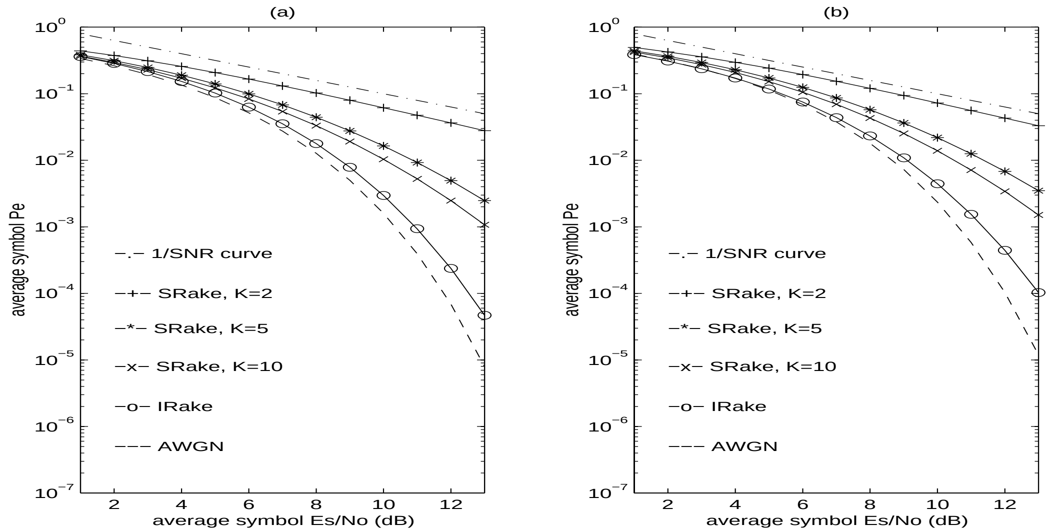

Fig. 1. The curves $\overline{UBP}_e\left(\frac{E_a}{N_o}\right)$ and $\overline{UBP}_e^{(K)}\left(\frac{E_a^K}{N_o}\right)$ for $K = 2, 5, 10$. (a) Performance of signal set (a) in equation 32. (b) Performance of signal set (b) in equation 32.

used. The figure also includes the performance curves of the signal sets in AWGN.

VI. DISCUSSION OF RESULTS

The use of M-TSK signals with $M = 4$ allows to double the data transmission rate without increasing the transmission bandwidth. With respect to performance, from figure 1 we see that performance in multipath using a selective Rake with $K > 10$ is about 2 dB worse than performance in multipath using an infinite Rake, and this performance is in turn about 1 dB worse than performance in AWGN using a correlator. These results suggest that the minimum K to be used is dictated by the amount of energy captured in K paths, and not by degradation in the selective Rake receiver. The issue of how much of the total energy is captured in K paths is addressed in [12].

References

[1] H. Hashemi, *"The Indoor Radio Propagation Channel,"* Proceedings of the IEEE Vol. 81 No. 7, July 1993.

[2] G. L. Stuber, *Principles of Mobile Communications,* KAP, 1996.

[3] R. Price and P. E. Green, Jr., *"A Communication Technique for Multipath Channels,"* Proc. IRE, March 1958, pp. 555-570.

[4] J. Schandle, *" Impulse Radio System Bid for PCS Communications Role,"* Electronic Design, February 4, 1993, pp. 32-34.

[5] R. A. Scholtz, *"Multiple Access with Time Hopping Impulse Modulation,"* invited paper, Proceedings of Milcom 93, Dec. 1993.

[6] R. A. Scholtz and M. Z. Win, *"Impulse Radio,"* invited paper, Proceedings of PIRMC 97, Sep. 1997.

[7] F. Ramírez-Mireles, M. Z. Win and R. A. Scholtz, *"Signal Selection for the Indoor Wireless Impulse Radio Channel,"* Proceedings of IEEE VTC'97, May 1997.

[8] J. M. Proakis, *Digital Communications,* McGraw Hill, 1995.

[9] M. Z. Win and R. A. Scholtz, "Statistical Characterization of Ultra-Wide Bandwidth Wireless Indoor Communications Channel," Proceedings of 31^{st} Asilomar Conference, Nov. 1997.

[10] J. M. Wozencraft and I. M. Jacobs, *Principles of Communication Engineering,* John Wiley, 1965.

[11] M. Z. Win and R. A. Scholtz, *"Ultra-Wide Bandwidth (UWB) Signal Propagation for Indoor Wireless Communications,"* Proceedings of IEEE ICC'97, June 1997.

[12] M. Z. Win and R. A. Scholtz, *"Energy capture Vs. Correlator Resources in Ultra-Wide Bandwidth Indoor Wireless Communications channels,"* Proceedings of Milcom 1997 conference, Nov. 1997.