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TR2003-65 August 2003

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Publication History:

1. First printing, TR-2003-65, August 2003

Effects of Spreading Bandwidth on the Performance of UWB Rake Receivers

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***Abstract*— We consider an ultra-wide bandwidth system using reduced-complexity Rake receivers, which are based on either selective (called SRake) or partial (called PRake) combining of a subset of the available resolved multipath components. We investigate the influence of the spreading bandwidth on the system performance using the two considered types of Rake receivers. We show that, for a fix number of Rake fingers and a fix transmit power, there is an optimum bandwidth. This optimal bandwidth increases with the number of Rake fingers, and is higher for an SRake than for a PRake. We also investigate the effects of the fading statistics (Rayleigh or Nakagami) on the optimal spreading bandwidth. We find that the optimal spreading bandwidth is approximately the same for both types of fading, but that the actual performance of an SRake can be better or worse in Rayleigh fading (compared to Nakagami), depending on the spreading bandwidth and the number of fingers.**

I. INTRODUCTION

Ultra-wide bandwidth (UWB) spread - spectrum (SS) multiple access techniques have recently received considerable attention for future commercial and military wireless communication systems [1]–[13]. Commonly, these radios [1]–[3] communicate with trains of short duration pulses with a low duty-cycle, and thus spread the energy of the radio signal very thinly over a wide range of frequencies. This provides inherent ability to resolve multipath components having differential delays of the order of nanoseconds (approximately equal to the inverse of the spreading bandwidth), which makes UWB SS radio a viable candidate for wireless communications in dense multipath environments [14], [15]. The potential strength of the UWB radio technique lies in its use of extremely wide transmission bandwidths, which results in desirable capabilities including accurate position location and ranging, lack of significant fading, multiple access, covert communications, and possible easier material penetration. The ability to resolve multipath components essentially transform dense multipath channels and creates a high degree of path diversity that can be utilized by a Rake like architecture.

For an ideal Rake receiver, spreading bandwidth should be as wide as possible, as it reduces the amount of fading seen by the detector. However, for a finite-complexity receiver, smaller spreading bandwidths might be preferable [16]–[19]. In a recent paper [20], we proposed simplified Rake receiver structures and analyzed their performance in UWB channels.

In this paper, we analyze the effect of spreading bandwidth on the performance of these structures in realistic UWB channels. We establish that, for a fix number of Rake fingers and a fix transmit power, there is an optimum bandwidth and that it increases with the number of Rake fingers. We also investigate the effects of the fading statistics on the optimal spreading bandwidth. We compare results of a simple Rayleigh-fading model to a model whose amplitude statistics are based on extensive measurement campaigns.

The rest of the paper is organized as follows: in Section II, we describe the different types of Rake receivers - ARake, SRake, and PRake. Next, we describe the channel model and give its parameters required for actual implementation. We then describe the simulation procedure used to obtain the bit error probability (BEP). We finally present the BEP for coherent detection of binary pulse-position modulated (B-PPM) signals using the SRake and PRake for different spreading bandwidth and different fading statistics.

II. The Rake Receivers

The basic version of the Rake receiver consists of multiple correlators (fingers) where each of the fingers can detect/extract the signal from one of the multipath components provided by the channel. The outputs of the fingers are appropriately weighted and combined to reap the benefits of multipath diversity. The equivalent matched filter version of the receiver involves a matched front-end processor (MFEP) (matched only to the transmitted waveform) followed by a tapped delay line and a combiner [16]–[18], [21]. The MFEP resolves multipath components whose delays differ by at least one chip duration, T_c, approximately equal to the inverse of the spreading bandwidth. The MFEP output is passed through a tapped delay line filter with L_r taps. As in [21]–[24], we consider the maximal-ratio combining of the diversity paths provided by the output of the taps.[1]

The term *all Rake (ARake)* has been largely used in the literature [16]–[18] to indicate the receiver with unlimited resources (taps or correlators) and instant adaptability, so that it can, in principle, combine *all* of the resolved multipath components [21]–[24]. To achieve this, it requires $L_r = T_d/T_c$ taps, where T_d is the maximum excess delay from the instant at which the first path arrives. Since the number of resolvable components increases with the spreading bandwidth, the number of correlators required for the ARake receiver may be quite large for UWB channels. However, the number of multipath components that can be utilized in a typical Rake combiner is limited by power consumption, design complexity and the channel estimation.

Complexity and performance issues have motivated studies of multipath combining receivers that process only a *subset* of the available L_r resolved multipath components but achieve better performance than a single path receiver. We consider two such reduced-complexity Rake receivers that are referred to as *selective Rake (SRake)* receivers and *partial Rake (PRake)* receivers. The SRake receiver selects the L_b best paths (a *subset* of the L_r available resolved multipath components) and then combines the selected subset using maximal-ratio combining [16]–[18]. This receiver makes the best use of its L_b available fingers, however selection procedure requires the knowledge of the instantaneous values of all multipath components. Due to the propagation properties of UWB signals, a good tradeoff between performance degradation and receiver complexity is provided by the simpler PRake. The PRake uses only L_p paths out of L_r available diversity paths, but it combines the *first* L_p arriving paths, which are not necessarily the best. The complexity reduction with respect to the SRake is due to the absence of a selection mechanism. Thus it does not need to sort the multipath components by the magnitude of their instantaneous path gains, which would require instantaneous and highly accurate channel estimation. The PRake only needs to find the position of the first arriving path, which leads to a substantial complexity reduction.

[1] Maximum ratio combining is optimum for noise-limited systems with ideal properties of the autocorrelation function of the spreading sequence. In the following, we will assume that these conditions are fulfilled.

III. Channel Model

For the evaluation of the receiver performance, we require an accurate model for the UWB propagation channel. We adopt the stochastic tapped delay-line propagation model for UWB indoor channels that we proposed in [25], and which is based on a measurement campaign in a typical office building. It characterizes the shape of the power-delay profile (PDP) of the UWB indoor channel in terms of path gains and delays of multipath components, i.e., by the pairs $\{G_k, \tau_k\}$, with $\tau_k = (k-1)\Delta\tau$, where $\Delta\tau = 2$ ns is the resolution of the considered system. Note that we have translated the delay axis by the delay of the direct or quasi line-of-sight (LOS) path given according to the geometry: $\tau_{\text{Ref}} = d/c$, where d is the transmitter-receiver (Tx-Rx) separation distance and c is the speed of light. Therefore, the delay bin of the first quasi LOS path begins at $\tau_1 = 0$.

The model prescribes the statistics of the path gains and its dependence on the delays τ_k. We distinguish between the *large* and *small* scale fading statistics. The large scale fading characterizes the changes in the received signal when the receiver position varies over a significant fraction of the Tx-Rx distance and/or the environment around the receiver changes significantly. The average PDP is specified according to

$$\overline{G}(\tau) = \frac{\overline{G}_{\text{tot}}}{1+\frac{r}{1-\exp(-\Delta\tau/\varepsilon)}} \Bigg\{ \delta(\tau-\tau_1) + \sum_{k=2}^{L_r} \left[r e^{-\frac{(\tau_k-\tau_2)}{\varepsilon}} \right] \delta(\tau-\tau_k) \Bigg\} . \qquad (1)$$

where the parameters $\overline{G}_{\text{tot}}$, r, and ε are defined in Table I. The small-scale fading, on the other hand, characterizes the changes in the received signal when the receiver position changes only of a small fraction of the Tx-Rx distance, while the environment around the receiver does not change

TABLE I

STATISTICAL MODELS AND PARAMETERS

GLOBAL PARAMETERS $\Rightarrow \overline{G}_{\text{tot}}$ and $\overline{G}_k$		
Path Loss (PL)	$20.4 \log_{10}\left(\frac{d}{d_0}\right)$	$d \leq 11\text{m}$
	$-56 + 74 \log_{10}\left(\frac{d}{d_0}\right)$	$d > 11\text{m}$
Shadowing	$\overline{G}_{\text{tot}} \sim \mathcal{L}_N\left(-PL\,;\,4.3\right)$	
Decay Constant	$\varepsilon \sim \mathcal{L}_N\left(16.1; 1.27\right)$	
Power Ratio	$r \sim \mathcal{L}_N\left(-4.0;\, 3.0\right)$	
LOCAL PARAMETERS $\Rightarrow G_k$		
Energy Gains	$G_k \sim \Gamma\left(\overline{G}_k;\, m_k\right)$	
m values	$m_k \sim \mathcal{T}_N\left(\mu_{\text{m}}(\tau_k);\, \sigma^2_{\text{m}}(\tau_k)\right)$	
	$\mu_{\text{m}}(\tau_k) = 3.5 - \frac{\tau_k}{73}$	
	$\sigma^2_{\text{m}}(\tau_k) = 1.84 - \frac{\tau_k}{160}$	

significantly. The *local path gains* $G_k = G(\tau_k)$ are Gamma-distributed random variables with mean $\overline{G}_k = \overline{G}(\tau_k)$ and parameter $m_k = m(\tau_k)$. Those m_k are themselves independent truncated Gaussian r.v.'s with parameters that depend on the delay τ_k; the actual values can be found in Table I. For more details and an implementation recipe of the model, we refer to [25].

IV. THE BIT ERROR PROBABILITY

A. Semi-analytical evaluation

We evaluate the BEP of the SRake and PRake structures in the realistic UWB channel, considering an uncoded system. We assume that the fading is sufficiently slow compared to the *symbol* duration (i.e., the inverse of the channel Doppler frequency is smaller than the symbol rate). In that case, the BEP is obtained by averaging the conditional BEP $P_{\text{e}|\gamma_{\text{b}}}(\cdot)$ (conditioned on the received instantaneous SNR per bit γ_{b}), over the probability density function (pdf) $p_{\gamma_{\text{b}}}(\cdot)$ of the instantaneous (local) SNRs at the Rake output [21]:

$$P_{\text{e}} = \int_0^\infty P_{\text{e}|\gamma_{\text{b}}}(x) p_{\gamma_{\text{b}}}(x) dx\,. \tag{2}$$

Thus, the first step for the BEP computations is to obtain the pdf of the SNR at the output of the Rake receiver. This distribution is obtained from computer experiments (Monte Carlo simulations) based on the channel model. We generate channel realizations at random, and extract the L_{b} (L_{p}) strongest (first) paths for the SRake (PRake). Adding the SNRs at those paths, corresponding to maximal-ratio combining, gives the SNR at the Rake output. We then perform a semi-analytical calculation of the BEP, by averaging the conditional BEP $P_{\text{e}|\gamma_{\text{b}}}(\cdot)$ over the channel ensemble, computed over one thousand realizations of the channel impulse response for different average SNR values.

B. BEP vs the Spreading Bandwidth

We now investigate the influence of the spreading bandwidth on the system performance. As the spreading bandwidth increases, we anticipate two counter-acting effects:[2]

- The signal energy is dispersed among more diversity paths, hence the amount of energy captured by a Rake receiver with a fixed number of fingers decreases. The decrease in SNR increases the BEP.
- The diversity gain increases with the spreading bandwidth. This is obvious for the ARake, as the number of diversity paths is directly proportional to the spreading bandwidth. The diversity gain also increases with spreading bandwidth for the SRake and the PRake, though the reasons in those cases are subtly different, as explained below.

Depending on the strength of those two effects, we can anticipate a BEP-vs-bandwidth curve that exhibits either a minimum or a monotonic behavior.

Let us now turn to the reasons for performance improvement of SRake and PRake as spreading bandwidth increases.

- For the SRake, the number of combined diversity paths L_{b} remains fixed. However, in a dense multipath channel, the number of resolvable multipaths increases with the spreading bandwidth. This implies that the number of the available diversity paths, L_{r}, out of which the SRake chooses to combine the diversity paths increases. Hence, the probability that all of the combined paths fade simultaneously decreases, and consequently, the BEP performance improves.
- For the PRake, the diversity gain is related to the PDP. In general, the diversity gain is highest for a uniform PDP, while only few "diversity branches" carry significant energy for a strongly decreasing PDP. Note that the distribution of the energy among the resolved multipath varies with the bandwidth. In the extreme case of a narrowband system, only a single finger captures energy. For a very wide bandwidth system, the resolvable multipath is very narrow (compared to the delay spread), so that all of the fingers in PRake are placed within a small fraction of the PDP. Thus, all fingers capture (on average) almost the same amount of energy, which leads to the highest effective diversity gain. Since higher diversity gain means

[2]Theoretical analyses of the effect of spreading bandwidth have been given for Rayleigh-fading in [16]–[19].

lower probability of fading dips, the BEP performance improves.

The loss in received signal energy increases essentially unlimited as we increase the spreading bandwidth.[3] On the other hand, the BEP improvement due to diversity order saturates. All of this implies the existence of an optimum bandwidth that minimizes the BEP. Fig. 1 plot the BEP as a function of the spreading bandwidth for different numbers of Rake fingers. We find that there is indeed an optimum bandwidth. Results also show that the optimum spreading bandwidth increases with the numbers of Rake fingers (for very high numbers of Rake fingers, the optimum is not visible on the plot anymore). This is intuitively clear, as more fingers are capable of collecting the energy provided by a larger number of resolved paths.

We also note that some of the BEP curves merge at low spreading bandwidths. This occurs if only a few paths carry noticeable energy. For low spreading bandwidth, only few multipath components of the channel are resolved, so that having more fingers does not give an additional advantage. For example, suppose that only 10 paths carry energy. Then it does not matter whether 16, 32, or more fingers are available - only 10 can be used anyway, the weight of the others is set to zero.

It is clear that SRake outperforms PRake. The difference in the performance decreases as the number of fingers increases. For the SRake the optimum bandwidth is at higher values - with the selective combining, it is more important to get the additional diversity (even at the price of sacrificing mean collected energy).

Fig. 2 also show the BEP as a function of bandwidth for an equivalent Rayleigh fading channel, i.e., a channel similar to the one described in Sec. III, but with $m_k = 1$ for all taps. In both cases, Nakagami and Rayleigh fading, the optimum spreading bandwidth is almost the same. However, the performance in terms of BEP depends on the fading statistics. At high spreading bandwidths, and for a small number of fingers, performance of the SRake is superior for Rayleigh fading. This seems astonishing at first glance, as the Nakagami channel exhibits less fading, and is thus usually considered to be "better behaved". However, if we choose the best L_b out of L_r paths with $L_\mathrm{b}/L_\mathrm{r} << 1$, it is actually advantageous if the per-path amplitude distribution has a large variance, because the receiver will select a path in the "high-

[3]Note that this argument is valid for a fixed transmit power. For a fixed transmit power spectral density, the energy collected by a fixed number of fingers stays approximately constant.

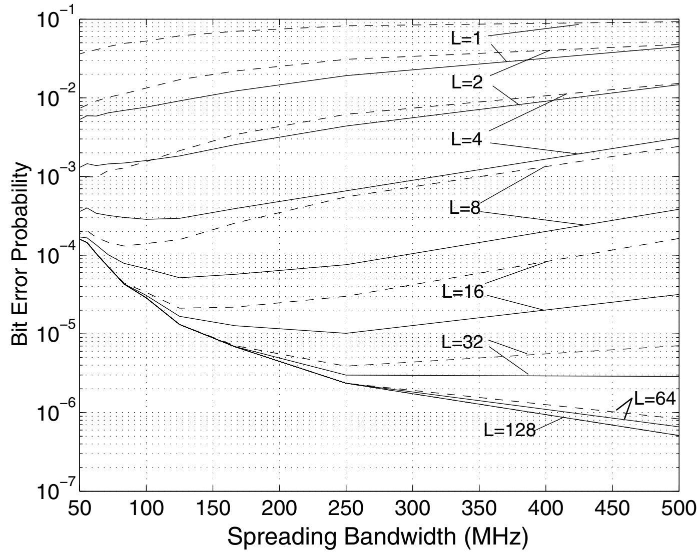

Fig. 1. The BEP vs the spreading bandwidth for different number of partial (dashed lines) and selective (solid lines) Rake fingers. The receiver is placed at 6m distance from the transmitter and the SNR at 1m is set to 30dB.

amplitude" tail of the probability density function. If, however, $L_\mathrm{b}/L_\mathrm{r}$ becomes sufficiently large, an amplitude distribution with less variations becomes more preferable. This explains why the "crossover" point in Fig. 2 occurs at larger spreading bandwidths as the number of Rake fingers increases.

Finally, we note that the optimum bandwidth for an SRake receiver is always higher than for a PRake. This can be explained by the fact that the average energy capture is higher for the SRake, so that more spreading can be used before the energy loss becomes prohibitive.

V. Conclusions

We analyzed the performance of low-complexity Rake receivers in a realistic UWB channel for different spreading bandwidths. We analyzed SRake and PRake receivers in channels that exhibit both large-scale and small-scale fading, with either Rayleigh or Nakagami fading. Our main results are:

- An optimum bandwidth, i.e., a spreading bandwidth that minimizes the BEP, exists.
- The optimum spreading bandwidth increases with the number of Rake fingers.
- An SRake receiver always outperforms PRake, but the difference decreases as the number of fingers increases.
- Optimum bandwidth for an SRake is higher than for a PRake.
- Optimum spreading bandwidth is almost the same for Rayleigh and Nakagami fading.

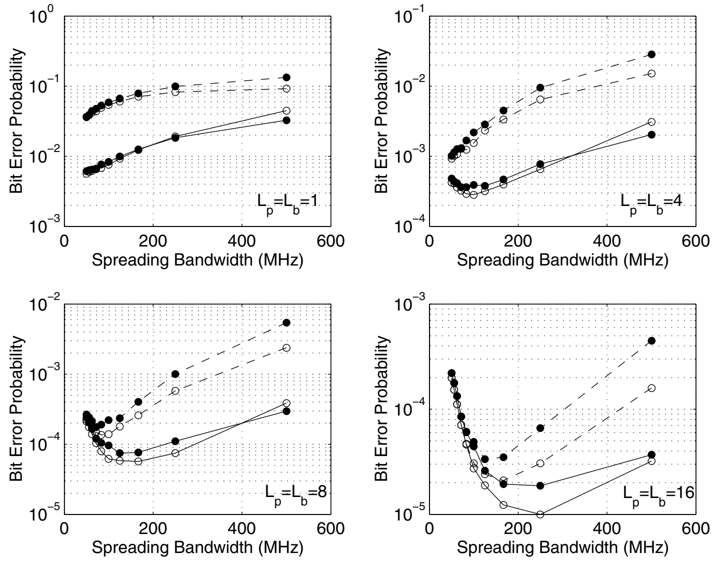

Fig. 2. The BEP vs the spreading bandwidth for different number of partial (dashed lines) and selective (solid lines) Rake fingers. The circles marked lines represents the BEP when the channel is Nakagami, while the dots marked lines the BEP when the channel is Rayleigh. The receiver is placed at 6m distance from the transmitter and the SNR at 1m is set to 30dB.

- For a low ratio $L_\mathrm{b}/L_\mathrm{r}$, performance of an SRake in a Rayleigh fading channel is better than in a Nakagami fading channel. For high ratios $L_\mathrm{b}/L_\mathrm{r}$, performance in Nakagami fading is better.

These results allow important conclusions about the optimal spreading bandwidth for practical systems.

References

[1] M. Z. Win and R. A. Scholtz, "Impulse radio: How it works," *IEEE Commun. Lett.*, vol. 2, pp. 36–38, Feb. 1998.

[2] M. Z. Win and R. A. Scholtz, "Comparisons of analog and digital impulse radio for multiple-access communications," in *Proc. IEEE Int. Conf. on Commun.*, vol. 1, pp. 91–95, June 1997. Montréal, CANADA.

[3] M. Z. Win and R. A. Scholtz, "Ultra-wide bandwidth time-hopping spread-spectrum impulse radio for wireless multiple-access communications," *IEEE Trans. Commun.*, vol. 48, pp. 679–691, Apr. 2000.

[4] Moe Z. Win and Robert A. Scholtz, "Characterization of ultra-wide bandwidth wireless indoor communications channel: A communication theoretic view," *IEEE J. Select. Areas Commun.*, vol. 20, no. 9, pp. 1613–1627, Dec. 2002.

[5] Moe Z. Win, "A unified spectral analysis of generalized time-hopping spread-spectrum signals in the presence of timing jitter," *IEEE J. Select. Areas Commun.*, vol. 20, no. 9, pp. 1664–1676, Dec. 2002.

[6] G. D. Weeks, J. K. Townsend, and J. A. Freebersyser, "Performance of hard decision detection for impulse radio," in *Proc. Military Comm. Conf.*, vol. 2, pp. 1201–1206, Oct. 1999. Atlantic City, NJ.

[7] J. Conroy, J. L. LoCicero, and D. R. Ucci, "Communication techniques using monopulse waveforms," in *Proc. Military Comm. Conf.*, vol. 2, pp. 1181–1185, Oct. 1999. Atlantic City, NJ.

[8] H. Lee, B. Han, Y. Shin, and S. Im, "Multipath characteristics of impulse radio channels," in *Proc. 50th Annual Int. Veh. Technol. Conf.*, vol. 3, pp. 2487–2491, 2000. Tokyo, JAPAN.

[9] C. J. Le Martret and G. B. Giannakis, "All-digital PAM impulse radio for multiple-access through frequency-selective multipath," in *Proc. IEEE Global Telecomm. Conf.*, vol. 1, pp. 77–81, Nov. 2000.

[10] J. R. Foerster, "The effects of multipath interference on the performance of UWB systems in an indoor wireless channel," in *Proc. IEEE Semiannual Veh. Technol. Conf.*, vol. 2, pp. 1176–1180, May 2001. Rhodos, GREECE.

[11] X. Huang and Y. Li, "Generating near-white ultra-wideband signals with period extended PN sequences," in *Proc. IEEE Semiannual Veh. Technol. Conf.*, vol. 2, pp. 1184 –1188, May 2001. Rhodos, GREECE.

[12] L. Zhao, A. M. Haimovich, and H. Grebel, "Performance of ultra-wideband communications in the presence of interference," in *Proc. IEEE Int. Conf. on Commun.*, vol. 10, pp. 2948–2952, June 2001. Helsinki, FINLAND.

[13] M. L. Welborn, "System considerations for ultra-wideband wireless networks," in *Proc. IEEE Radio and Wirless Conf.*, pp. 5–8, Aug. 2001. Boston, MA.

[14] M. Z. Win and R. A. Scholtz, "On the robustness of ultra-wide bandwidth signals in dense multipath environments," *IEEE Commun. Lett.*, vol. 2, pp. 51–53, Feb. 1998.

[15] M. Z. Win and R. A. Scholtz, "On the energy capture of ultra-wide bandwidth signals in dense multipath environments," *IEEE Commun. Lett.*, vol. 2, pp. 245–247, Sept. 1998.

[16] M. Z. Win and Z. A. Kostić, "Virtual path analysis of selective Rake receiver in dense multipath channels," *IEEE Commun. Lett.*, vol. 3, pp. 308–310, Nov. 1999.

[17] M. Z. Win, G. Chrisikos, and N. R. Sollenberger, "Performance of Rake reception in dense multipath channels: Implications of spreading bandwidth and selection diversity order," *IEEE J. Select. Areas Commun.*, vol. 18, pp. 1516–1525, Aug. 2000.

[18] M. Z. Win and G. Chrisikos, "Impact of spreading bandwidth and selection diversity order on selective Rake reception," in *Wideband Wireless Digital Communications* (A. F. Molisch, ed.), (Upper Saddle River, New Jersey 07458), pp. 424–454, Prentice Hall Publishers, 2001.

[19] W. C. Lau, M.-S. Alouini, and M. K. Simon, "Optimum spreading bandwidth for selective Rake reception over Rayleigh fading channels," *IEEE J. Select. Areas Commun.*, vol. 19, pp. 1080–1089, June 2001.

[20] D. Cassioli, M. Z. Win, F. Vatalaro, and A. F. Molisch, "Performance of selective Rake reception in a realistic UWB channel," in *Proc. IEEE Int. Conf. on Commun.*, vol. 2, pp. 763–767, May 2002. New York, NY.

[21] J. G. Proakis, *Digital Communications*. New York, NY, 10020: McGraw-Hill, Inc., fourth ed., 2001.

[22] D. L. Noneaker and M. B. Pursley, "On the chip rate of CDMA systems with doubly selective fading reception," *IEEE J. Select. Areas Commun.*, vol. 12, pp. 853–861, June 1994.

[23] D. Goeckel and W. Stark, "Performance of coded direct-sequence systems with Rake reception in a multipath fading environment," *European Trans. on Telecommun., Special Issue on Spread Spectrum Techniques*, vol. 6, pp. 41–52, Jan.-Feb. 1995.

[24] T. Eng and L. B. Milstein, "Coherent DS-CDMA performance in Nakagami multipath fading," *IEEE Trans. Commun.*, vol. 43, pp. 1134–1143, Feb./Mar./Apr. 1995.

[25] 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, Aug. 2002.