Optimization of Energy Detector Receivers for UWB Systems

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***Abstract*— Practical and low complexity implementation of receivers is of vital importance for the successful penetration of the ultrawideband (UWB) technology. Energy detector receiver is an attractive solution for UWB signal reception trading off complexity with performance. In this paper, joint estimation of the optimal threshold, synchronization point, and integration interval for energy detection based ultrawideband signal reception with on-off keying (OOK) modulation is developed. Suboptimal reception derived from the optimal solution is also given for practical implementations. Gaussian approximation of the received signal statistics enables low complexity solutions at the expense of some performance degradation. The performances of the optimal and suboptimal solutions are evaluated and compared.**[1]

I. Introduction

Ultrawideband (UWB) is a promising technology for future short-range, high-data rate wireless communication networks. Compared to other communications systems, UWB is unique in that it has the exciting feature of combining many desired characteristics like the increased potential of achieving high data rates, low transmission power requirement, and immunity to multipath effects.

Coherent receivers (such as RAKE and correlator receivers) are commonly used for UWB signal reception due to their high power efficiencies. However, implementation of such receivers requires estimation of *a priori* channel information regarding the timing, fading coefficient, and the pulse shape for each individual channel tap. Coherent signal reception also stipulates high sampling rates and accurate synchronization. On the other hand, non-coherent receivers have less stringent *a priori* information requirements and can be implemented with lower complexity. For example, in transmitted reference (TR) receivers, transmission of the reference pulse(s) (which includes the channel information) to correlate the information bearing pulse(s) eliminates the need for estimating the channel parameters.

Energy detector is another non-coherent approach for ultrawideband (UWB) signal reception, where low complexity receivers can be achieved at the expense of some performance degradation [1], [2]. As opposed to more complex RAKE receivers, estimation of individual pulse shapes, path amplitudes, and delays at each multipath component is not necessary for energy detectors. Moreover, energy detectors are less sensitive against synchronization errors [3], and are capable of collecting the energy from all the multipath components. On-off keying (OOK) is one of the most popular non-coherent modulation options that has been considered for energy detectors. OOK based implementation of energy detectors is achieved by passing the signal through a square law device (such as a Schottky diode operating in square-region) followed by an integrator and a decision mechanism, where the decisions are made by comparing the outputs of the integrator with a threshold. Two challenging issues for the enhancement of energy detector receivers are the estimation of the optimal threshold [1], [4], and the determination of synchronization/dump points of the integrator. The effect of integration interval on the system performance has been analyzed before for energy detectors [2], and for transmitted reference (TR) based non-coherent receivers [5]-[7]. In this work, a practical and adaptive receiver design for UWB signal transmission is developed. An energy detector receiver that estimates the optimal decision threshold and integration parameters is discussed. Suboptimal solutions which allow practical and simple implementations with slight performance degradation are also provided.

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II. System Model

Let the impulse radio (IR) based UWB signal received for bit i in a multipath environment be represented as

$$r_i(t) = \sum_{j=1}^{N_s} \big(s_j(t) + n_j(t)\big) \ , \tag{1}$$

where we have

$$s_j(t) = \sum_{l=1}^{L} \gamma_L b_i \omega_l\big(t - jT_f - c_j T_c - \tau_l\big) \ , \tag{2}$$

the number of pulses per symbol is denoted by N_s, L is the number of multipath components arriving at the receiver, j and l are the frame and tap indices, respectively, b_i is the ith transmitted bit with OOK modulation, $\omega_l(t)$ is the received pulse shape for the lth path, T_f is the frame duration ($T_f > \tau_L > T_c$), c_j are the time-hopping codes, γ_l and τ_l are the fading coefficient and the delay of the lth multipath component, respectively and T_c is the chip duration. The additive white Gaussian noise (AWGN) with double-sided noise spectral density $N_0/2$ is denoted by $n_j(t)$. The received signal is passed through a bandpass filter of bandwidth B to capture the significant portion of signal spectrum while removing out-of-band noise and interference, resulting in $\tilde{s}_j(t),\ \tilde{n}_j(t)$.

Now consider an energy detector, where the following decision statistic is used to make a symbol detection by sensing

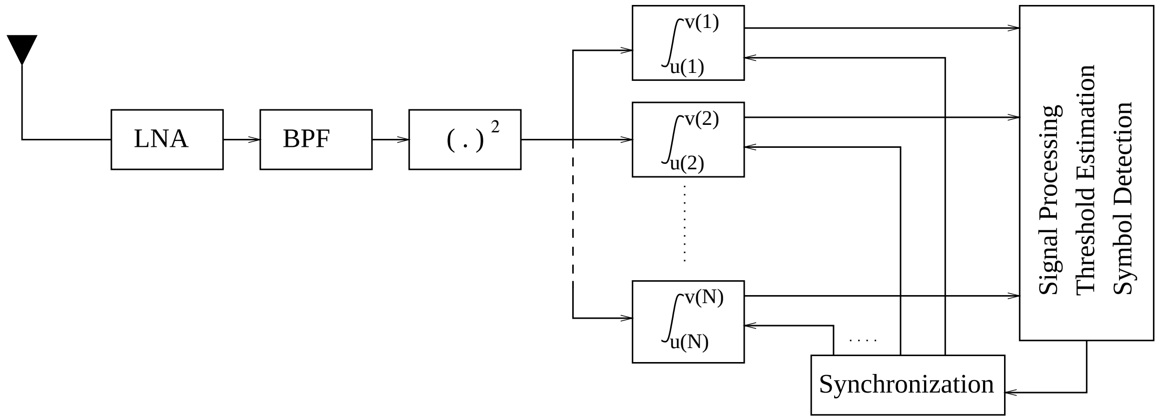

Fig. 1. Adaptive parameter estimation for energy detector receivers.

if there is energy or not within the symbol interval

$$h_i = \sum_{j=1}^{N_s} \int_{T_i} \Big[\sum_{l=1}^{L} \gamma_L b_i \omega_l \big(t - jT_f - c_j T_c - \tau_l \big) + \tilde{n}_j(t) \Big]^2 dt \ , \tag{3}$$

where T_i is the integration window defined by synchronization and dump points (u, v). In other words, the above approach for the energy detector integrates the square of the received signal for each pulse position over the maximum excess delay of the channel, and sums these statistics over N_s pulses. The symbol decision is performed by comparing h_i with a threshold ξ, $h_i \gtrless_0^1 \xi$.

Observing (3), it is seen that optimal (joint) estimation of (u, v, ξ) is of critical importance for the performance of energy detectors, as will be discussed throughout the rest of this paper.

III. Proposed Receiver

Since the radio channel characteristics change in time, an adaptive energy detector receiver design that optimizes the performance depending on the variation of the channel is needed. The proposed adaptive receiver, which is designed in such a way to fulfill this requirement, is shown in Fig. 1. In this receiver, the received signal is amplified, band pass filtered, squared, and passed through a bank of parallel integrators. The reason for employing multiple parallel integrators, each with a different time constant, is to select the integration interval that minimizes the bit error rate (BER). Using the training bits, that are periodically inserted in between data symbols, a synchronization point (the starting point of the multipath energy) is estimated over each branch, and an optimum short-term threshold is evaluated. Synchronization and optimum threshold determination are achieved by estimating the signal and noise statistics (like signal and noise power) during the training period. These statistics are then used for relating the expected BER performance of each branch. Note that increasing the number of the parallel integrator branches, in effect, increases the 'integration time resolution' of the receiver and enhances the likelihood of obtaining a lower BER. However, this comes at the expense of computational and hardware complexity.

Note that as an alternative to employing multiple parallel integrator branches, optimal receiver parameters can also be evaluated by using a single integrator and larger number of training bits (to test multiple hypothesis), and storing the statistics for each hypothesis in a buffer for post processing.

A. Practical Estimation of Optimum Threshold

The optimal threshold in an energy detector receiver depends on the noise variance, multipath delay profile, received signal energy, integration interval, synchronization point, and the bandwidth of the bandpass filter. From the training samples, the *exact* optimal threshold $\xi_k^{(E)}$ can be calculated using the centralized and non-centralized Chi-square distributions, corresponding to bits 0 and 1, respectively, and where k denotes the integrator number. However, this requires a search over possible threshold values in order to find the one that minimizes the BER [4], or, high signal to noise ratio (SNR) assumption in order to use asymptotic approximation of the Bessel function (which still yields a threshold estimate based on tabulated data) [1]. It was shown in [8], [4] that by approximating the Chi-square distributions with Gaussian distributions, which becomes more valid for large degree of freedom (DOF) defined by $2M = 2BT_i + 1$, the threshold estimates $\xi_k^{(G)}$ can be obtained (as an approximation to $\xi_k^{(E)}$). Even though these estimates are not very accurate [4], they can be obtained easily, without requiring any search over possible threshold values. Let the means and variances of the Chi-square distributions for bits 0 and 1 be given by $\mu_0(k)$, $\sigma_0^2(k)$, $\mu_1(k)$, and $\sigma_1^2(k)$, respectively [4], [9], where

$$\mu_0(k) = MN_0 \tag{4}$$
$$\sigma_0^2(k) = MN_0^2 \tag{5}$$
$$\mu_1(k) = MN_0 + 2E_b \tag{6}$$
$$\sigma_1^2(k) = MN_0^2 + 4E_b N_0 \ . \tag{7}$$

The threshold estimate using the Gaussian approximation is located at the intersection of the two Gaussian distributions, which can be evaluated from

$$\frac{1}{\sqrt{2\pi\sigma_0^2(k)}} e^{-\frac{(\xi_k^{(G)} - \mu_0(k))^2}{2\sigma_0^2(k)}} = \frac{1}{\sqrt{2\pi\sigma_1^2(k)}} e^{-\frac{(\mu_1(k) - \xi_k^{(G)})^2}{2\sigma_1^2(k)}} \ . \tag{8}$$

Taking the natural logarithm of both sides and rearranging the terms, one obtains

$$C_1(\xi_k^{(G)})^2 + C_2\xi_k^{(G)} + C_3 = 0 \ , \tag{9}$$

where the coefficients are given by

$$C_1 = \sigma_1^2(k) - \sigma_0^2(k) \ , \tag{10}$$

$$C_2 = -2\Big(\mu_0(k)\sigma_1^2(k) - \mu_1(k)\sigma_0^2(k)\Big) \ , \tag{11}$$

$$C_3 = \sigma_1^2(k)\mu_0^2(k) - \sigma_0^2(k)\mu_1^2(k) - 2\sigma_0^2(k)\sigma_1^2(k)\ln\left(\frac{\sigma_1(k)}{\sigma_0(k)}\right) \ , \tag{12}$$

with (9) being a second order polynomial equation that can be easily solved for $\xi_k^{(G)}$ (only one of the roots is appropriate). The Gaussian approximation approach above is different from the one presented in [4], because here the noise variance is practically obtained from the training symbols instead of being taken as a given parameter. As an alternative to using frequent training symbols, the threshold can be updated (tracked) in a decision-directed manner once it is initially estimated.

B. Adaptation of Integration Interval and Calculation of BER

When implementing an energy detector, specifying an integration interval that sacrifices the insignificant multipath components in order to decrease the collected noise energy will improve the performance [6], [2]. For a better performance it is also significant that the receiver synchronizes with the starting point of the multipath energy. Therefore, the optimal interval, which minimizes the BER, can ideally be achieved by a joint and adaptive determination of the starting point and duration of integration.

The starting points and integration durations can be estimated by a synchronization algorithm that tests multiple integration intervals along with various starting points and jointly chooses both so that the BER is minimized. However, this method considerably increases the computational complexity of the receiver. A sub-optimal solution, where the initial point of the received signal is taken as the common starting point for all possible integration durations, yields very close performance to the optimal case when the power delay profile (PDP) of the channel realization is exponentially decaying. For example, the channel model CM1 in [10] reflects such a minimum phase scenario where single synchronization point performs as well. For dispersive channels (such as CM4) however, there will be some performance degradation.

Using the training bits, multiple hypothesis for the integration interval can be tested (using multiple integrators) and the one that minimizes the BER can be selected. Let $u(k)$ and $v(k)$ denote the starting and dump points of the kth integrator, respectively. Then, based on the energy and noise statistics for a particular integrator, either exact or Gaussian approximation (which is less complex but suboptimal) approaches can be used to evaluate the thresholds $\xi_k^{(E)}$ and $\xi_k^{(G)}$. In order to decrease the computational complexity, the serial search for $\xi_k^{(E)}$ can be performed in the range $(MN_0 + 0.5E_b, MN_0 + E_b)$, as the normalized threshold in most cases falls in between 0.25 and 0.5. The BER observed after each integrator for the two cases are then given by $P_b(k, \xi_k^{(E)})$ and $P_b(k, \xi_k^{(G)})$, respectively [1],

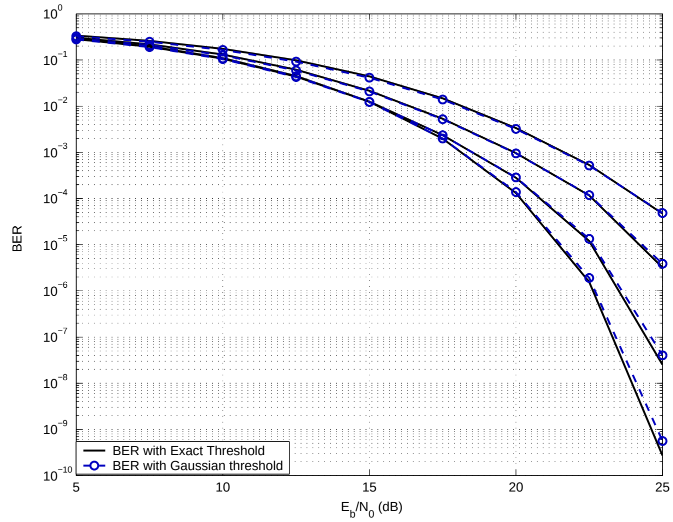

Fig. 2. Bit error rate vs. E_b/N_0 for different integration intervals ($T_i = 10, 20, 40, 60\ ns$ and $BW = 500\ MHz$) and for both Gaussian approximated and exact threshold estimates.

where

$$P_b(k, \xi_k) = P_{k,\xi_k}(0|1) + P_{k,\xi_k}(1|0) \ , \tag{13}$$

$$P_{k,\xi_k}(0|1) = 0.5 - 0.5\mathcal{Q}_M\left(\sqrt{\frac{4E_b}{N_0}}, \sqrt{\frac{2\xi_k}{N_0}}\right) \ , \tag{14}$$

$$P_{k,\xi_k}(1|0) = \frac{e^{-\frac{\xi_k}{N_0}}}{2}\sum_{u=1}^{\lfloor M \rfloor}\frac{(\xi_k/N_0)^{M-u}}{\Gamma(M-u+1)}, \tag{15}$$

the average energy received for bits 0 and 1 is denoted by E_b, $\mathcal{Q}_M$ is the generalized Marcum- $\mathcal{Q}$ function of order M, and $\Gamma(x)$ is the Gamma function which equals $(x-1)!$ for x integer. The optimum integrator is the one that minimizes the BER, i.e. $\underset{k}{\operatorname{argmin}}(P_b(k, \xi_k))$.

IV. Simulation Results

Computer simulations are done to analyze the performances of the proposed approaches. In these simulations the channel models in [10] are used and the received signal's bandwidth is taken as 2 GHz.

For each different integration interval, an exact threshold $\xi_k^{(E)}$ as well as a Gaussian approximated threshold $\xi_k^{(G)}$ is calculated. The BERs calculated for the two different cases, in which the exact and Gaussian thresholds are employed, respectively, are compared to each other. It is observed that the closeness of the two BERs depends on the bandwidth of the received signal. For large bandwidths, they obviously differ from each other, whereas for a relatively small bandwidth like 500 MHz, the BER values obtained making use of the Gaussian threshold mostly match with the exact BERs, as shown in Fig. 2. Therefore, one can take the advantage of computational easiness of the Gaussian approximation when setting the threshold if the received signal's bandwidth is small.

It is also found that the effect of determining the synchronization point adaptively is more critical for shorter integration intervals. For longer ones, this approach yields slight gains

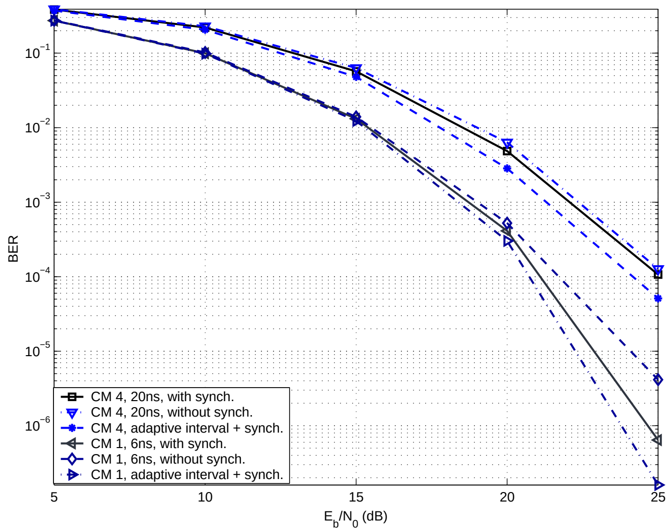

Fig. 3. BER vs. E_b/N_0 for randomly selected fixed integration intervals, adaptive integration interval, and adaptive synchronization point ($BW = 2\ GHz$).

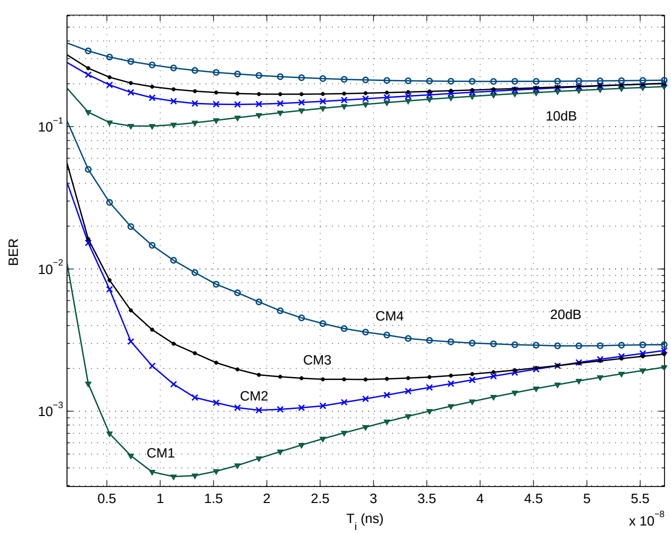

Fig. 4. BER vs. Optimum integration interval for different channel models ($BW = 2\ GHz$).

in CM4 (with almost identical performance for other channel models). In Fig. 3, BER is plotted with respect to E_b/N_0 for CM4 and CM1 for a *fixed* integration interval (synchronized and non-synchronized), as well as for the optimum integration interval.

Another observation is that the optimum integration interval changes substantially for different channel models, implying the fact that significant gains can be obtained for a mobile device when the integration interval is adaptively determined, as shown in Fig. 4. Variation of the optimal integration interval with respect to E_b/N_0 is plotted for different channel models in Fig. 5. The line-of-sight (LOS) component of CM1 yielding a parallel variation with CM2 is observed, together with CM3 and CM4 having larger optimal integration values (and slopes) due to more spread distribution of their multipath components over time.

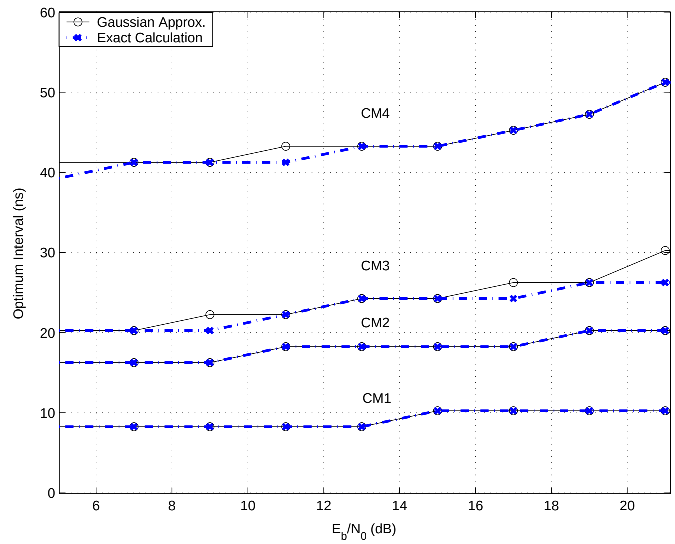

Fig. 5. Optimum integration interval vs. E_b/N_0 for different channel models ($BW = 2\ GHz$).

V. Conclusion

In this paper, optimization of adaptive energy detector receivers for UWB systems is discussed. The need for the joint adaptation of the integration interval, optimal threshold, and the synchronization point (for certain channels) is clearly demonstrated, which can be extended to other non-coherent approaches. Threshold estimation can benefit from the computational easiness brought by the Gaussian approximation of received signal statistics, which yields reasonable results for certain bandwidths.

There are some other issues related to the energy detector worth to be discussed before concluding. By averaging the noise over many pulses that represent a single bit, performance of energy detector receivers may be further enhanced. Secondly, considering the computational requirements for adaptive threshold determination, for some applications one may find it more reasonable to employ a *fixed long-term* threshold that takes the channel variations into account. UWB multipath components can be modeled with Nakagami-m distribution [11], [12], and are known to be composed of less diffuse (specular) components for the initial taps (with larger m parameter), and more diffuse components for the subsequent taps (with smaller m parameter). Once the signal passes through the square-law device in an energy detector, the distribution of the signal component (when a bit 1 is transmitted) will be due to the sum of squares of the fading coefficients [13]. Therefore, taking into account this new distribution (which is observable over many blocks in the long term), as well as the effect of noise, a long-term fixed threshold can be calculated.

References

[1] S. Paquelet, L. M. Aubert, and B. Uguen, "An impulse radio asynchronous transceiver for high data rates," in *Proc. IEEE Ultrawideband Syst. Technol. (UWBST)*, Kyoto, Japan, May 2004, pp. 1–5.

[2] M. Weisenhorn and W. Hirt, "Robust noncoherent receiver exploiting UWB channel properties," in *Proc. IEEE Ultrawideband Syst. Technol. (UWBST)*, Kyoto, Japan, May 2004, pp. 156–160.

[3] A. Rabbachin and I. Oppermann, "Synchronization analysis for UWB systems with a low-complexity energy collection receiver," in *Proc. IEEE Ultrawideband Syst. Technol. (UWBST)*, Kyoto, Japan, May 2004, pp. 288–292.
[4] P. A. Humblet and M. Azizoglu, "On the bit error rate of lightwave systems with optical amplifiers," *J. of Lightwave Technology*, vol. 9, no. 11, pp. 1576–1582, Nov. 1991.
[5] H. Akahori, Y. Shimazaki, and A. Kasamatsu, "Examination of the automatic integration time length selection system using PPM in UWB," in *Proc. IEEE Ultrawideband Syst. Technol. (UWBST)*, Kyoto, Japan, May 2004, pp. 268–272.
[6] S. Franz and U. Mitra, "Integration interval optimization and performance analysis for UWB transmitted reference systems," in *Proc. IEEE Ultrawideband Syst. Technol. (UWBST)*, Kyoto, Japan, May 2004, pp. 26–30.
[7] N. He and C. Tepedelenlioglu, "Adaptive synchronization for noncoherent UWB receivers," in *Proc. IEEE Acoustics, Speech, Signal Processing Conf. (ICASSP)*, Montreal, Canada, May 2004, pp. 517–520.
[8] J. Edell, "Wideband, noncoherent, frequency-hopped waveforms and their hybrids in low-probability of intercept communications," *Report Naval Research Laboratory (NRL) 8025*, Nov. 1976.
[9] R. Mills and G. Prescott, "A comparison of various radiometer detection models," *IEEE Trans. Aerospace Electron. Syst.*, vol. 32, no. 1, pp. 467–473, Jan. 1996.
[10] J. Foerster, "IEEE P802.15 working group for wireless personal area networks (WPANs), channel modeling subcommittee report - final," Mar. 2003. [Online]. Available: http://www.ieee802.org/15/pub/2003/Mar03/
[11] H. Urkowitz, "Energy detection of unknown deterministic signals," in *Proc. of IEEE*, vol. 55, no. 4, Apr. 1967, pp. 523–531.
[12] V. I. Kostylev, "Energy detection of a signal with random amplitude," in *Proc. IEEE Int. Conf. on Commun. (ICC)*, vol. 3, New York, Apr. - May 2002, pp. 1606–1610.
[13] M.-S. Alouini, A. Abdi, and M. Kaveh, "Sum of gamma variates and performance of wireless communication systems over Nakagami-fading channels," *IEEE Trans. Vehic. Technol.*, vol. 50, no. 6, pp. 1471–1480, Nov. 2001.