Error Performance of OOFSK Signaling over Fading Channels

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***Abstract*— In this paper, the error performance of on-off frequency-shift keying (OOFSK) over fading channels is analyzed. A closed-form expression for the probability of error is obtained as a function of the instantaneous signal-to-noise ratio (SNR) when OOFSK signals are received over a coherent Rician fading channel. It is shown in simulation results that error performance improves especially at low SNR values as the duty cycle decreases. The error performance is also studied when the channel is assumed to be unknown at both the transmitter and receiver. For this case, the optimum detection rule is identified and analytical expressions for the probability of error are obtained. Similarly, it is concluded that probability of error decreases if one operates with lower duty cycle.**

I. Introduction

Although efficient use of energy resources is a design challenge in most wireless systems where battery-operated mobile radio units are employed, recent interest in wireless ad-hoc and sensor networks has further increased concerns on energy efficiency [1], [2]. In wireless ad-hoc networks where mobile nodes are required to establish communication without the aid of a fixed infrastructure, network lifetime and connectivity are highly dependent on node longevity, which is controlled by the battery lifetime. In wireless sensor networks, sensor nodes should make efficient use of scarce energy resources. For instance, the specifications of a wireless microsensor system given in [3] indicate that the microsensors need to operate for 5-10 years with one AA size battery.

Since energy efficiency has to be sustained across all the layers of the protocol stack, communication techniques on the physical, medium access, and network layers have been proposed to improve the energy efficiency in wireless networks [13], [14], [15], [16]. Moreover, cross-layer design has emerged as a new paradigm with the goal of achieving even higher performance gains [4].

In this paper, we concentrate on the physical layer and analyze the performance of the recently-proposed modulation technique on-off frequency-shift keying (OOFSK) [11]. OOFSK is a modulation scheme in which frequency-shift keying (FSK) is overlaid on top of on-off keying (OOK). FSK is an commonly used modulation tehnique whose performance has been well studied. In [8], the error performance of the FSK modulated signal transmitted over Rician multiple reception channels has been investigated. It is shown that the probability of error decreases inversely with the increasing number of multichannels and Rician factor for coherent and noncoherent multiple receivers. Luo *et al.* [9] obtained upper and lower bounds for the probability of error of multi-tone FSK on wideband noncoherent Rayleigh fading channels where neither the transmitter nor the receiver has channel knowledge. In [10], circuit energy as well as transmission energy is considered and it is shown that the total energy consumption can be minimized by optimizing the active time T_{on}. Wang *et al.* [3] showed that when both the circuit and transmission energies are taken into account, FSK modulation has a much better performance in terms of energy efficiency when compared to phase-shift keying and quadrature amplitude modulation. One of the advantages of FSK is that if a direct modulation approach is used, savings from circuit energy is achieved by removing digital-to-analog converters, mixers, and quadrature voltage-controlled oscillators.

The capacity and cutoff rate of FSK modulation over Rician fading channels with a noncoherent receiver have been studied in [7]. The capacity and power efficiency of OOFSK have been studied in [11] where the channel capacity is computed for Rician fading channels with perfect or imperfect channel information at the receiver and it is shown that the minimum bit energy decreases if signals with higher peak-to-average power ratios are allowed.

In this paper, the error performance and energy efficiency of OOFSK signaling are studied. The organization of the paper is as follows. Section II introduces the channel model. Section III discusses the performance of OOFSK modulation over coherent fading channels. Section IV analyzes the performance of OOFSK over noncoherent fading channels while section V includes our conclusions.

II. Channel Model

If OOFSK signaling scheme is employed, transmitter sends over the time interval of $[0, T]$ either no signal with probability $1-v$ or one of the following M orthogonal sinusoidal signals with probability v:

$$s_k(t) = \sqrt{\frac{P}{v}} e^{j(w_k t + \theta_k)} \quad 1 \le k \le M \tag{1}$$

where P is the average power, w_k and θ_k are the frequency and phase of $s_k(t)$ respectively. The no signal case is denoted by $s_0(t) = 0$ for $0 \le t \le T$.

The channel is assumed to experience flat fading, i.e, delay spread of the fading is much less than symbol duration T. Moreover, it is assumed that T is less than the coherence time T_c. Under these assumptions, channel fading coefficient

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h stays constant during the symbol time. Hence, the received signal can be modeled as:

$$r(t) = hs_k(t) + n(t) \quad 0 \le t \le T \tag{2}$$

where $n(t)$ is a zero-mean circularly symmetric complex white Gaussian noise process with single-sided spectral density N_0. Without loss of generality, it is assumed that the k^{th} signal $s_k(t)$ is transmitted. A bank of M correlators is employed at the receiver and the output at time $t = T$ of the m^{th} correlator normalized by the noise energy is given by:

$$\begin{aligned} Y_m &= \frac{1}{\sqrt{N_0 T}} \int_0^T r(t) e^{-jw_m t} dt \\ &= \frac{1}{\sqrt{N_0 T}} \int_0^T \left[h\sqrt{\frac{P}{v}} e^{(w_k - w_m)t + \theta_k} + n(t) e^{-jw_m t} \right] dt \\ &= \begin{cases} \alpha h e^{j\theta_k} + n_m, & m = k \\ n_m, & m \ne k \end{cases}, m = 1, 2, \ldots, M, \end{aligned} \tag{3}$$

where n_m is a zero-mean unit-variance circularly symmetric complex Gaussian random variable and $\alpha = \sqrt{\frac{PT}{vN_0}}$. Note that since orthogonal signals are transmitted, $\{n_m\}$ forms a sequence of independent and identically distributed (i.i.d.) random variables. It is assumed that the receiver performs energy detection, and hence the decoder observes $R_m = |Y_m|^2$ for $m = 1, 2, \ldots, M$.

III. OOFSK Performance over Coherent Rician Fading Channels

For the Rician fading channel, h is a proper complex Gaussian random variable with mean d and variance γ^2. In this section, we assume that the magnitude h is perfectly known at the receiver. It is readily observed from (3) that

$$E\{Y_m | s_k, h, \theta_k\} = \alpha h e^{j\theta_k} \delta_{mk} \tag{4}$$

$$var\{Y_m | s_k, h, \theta_k\} = E|n|^2 = 1, \tag{5}$$

where $\delta_{mk} = 1$ if $m = k$ and 0 otherwise. Conditioned on s_k and $|h|$, $R_m = |Y_m|^2$ is a chi-square random variable with two degrees of freedom and the conditional probability density function (*pdf*) of R_m is given by

$$f(R_m | s_k, |h|) = \begin{cases} e^{-(\alpha^2|h|^2 + R_m)} I_0\left(2\sqrt{\alpha^2 |h|^2 R_m}\right) & m = k \\ e^{-R_m} & m \ne k \end{cases}$$

where $m \in \{1, \ldots, M\}$ and $k \in \{0, 1, \ldots, M\}$. Let $\mathbf{R}$ denote the vector of the output energies of the M correlators, i.e, $\mathbf{R} = [R_1, R_2, \ldots, R_M]$, then the joint conditional distribution function of M outputs is given by:

$$f(\mathbf{R} | s_k, |h|) = \begin{cases} e^{-\sum_{j=1}^M R_j} e^{-\alpha^2|h|^2} I_0\left(2\sqrt{R_k \alpha^2 |h|^2}\right) & 1 \le k \le M \\ e^{-\sum_{j=1}^M R_j} & k = 0 \end{cases} \tag{6}$$

Maximum a posteriori probability (MAP) decision rule is used for the detection of the OOFSK signals. Hence, $s_k(t)$ is the detected signal if the following condition is satisfied:

$$p(s_k) f(\mathbf{R} | s_k, |h|) > p(s_l) f(\mathbf{R} | s_l, |h|) \quad \forall l \ne k \tag{7}$$

where $p(s_k)$ is the prior probability of the message signal s_k. Note that, in OOFSK signaling we have $p(s_k) = \frac{v}{M}$ for $k \ne 0$ and $p(s_0) = 1 - v$. Therefore, using the prior probabilities and the joint conditional distribution function in (6), and assuming without loss generality that $k \ne 0$, we further simplify the detection rule as follows:

$$f(\mathbf{R} | s_k, |h|) > f(\mathbf{R} | s_l, |h|) \Longrightarrow R_k > R_l, \ \forall l \ne k, \tag{8}$$

and

$$\frac{v}{M} f(\mathbf{R} | s_k, |h|) > (1 - v) f(\mathbf{R} | s_0, |h|) \Longrightarrow R_k > T_h \tag{9}$$

where

$$T_h = \frac{\left[I_0^{-1}\left(\frac{M(1-v)e^{\alpha^2|h|^2}}{v} \right) \right]^2}{4\alpha^2 |h|^2}$$

is a threshold value and I_0^{-1} is the functional inverse of the zeroth order modified Bessel function of the first kind. Without loss of generality, assuming s_1 is the transmitted signal, we obtain the probability of error as the following:

$$\begin{aligned} P_{e1} &= 1 - P_{c1} \\ &= 1 - \int_{T_h}^{\infty} P(R_2 < R_1, \ldots, R_M < R_1 | R_1 = x) f_{R_1|s_1}(x|s_1) dx \\ &= 1 - \int_{T_h}^{\infty} (1 - e^{-x})^{M-1} e^{-(\alpha^2|h|^2 + x)} I_0\left(2\sqrt{\alpha^2|h|^2 x}\right) dx \\ &= 1 - \sum_{n=0}^{M-1} (-1)^n \binom{M-1}{n} \int_{T_h}^{\infty} e^{-nx} e^{-(\alpha^2|h|^2 + x)} I_0\left(2\sqrt{\alpha^2|h|^2 x}\right) dx \end{aligned} \tag{10}$$

where the last equality is obtained by using the binomial expansion

$$(1 - e^{-x})^{M-1} = \sum_{n=0}^{M-1} \binom{M-1}{n} (-1)^n e^{-nx}. \tag{11}$$

The Marcum Q-function is defined as:

$$Q_1(\alpha, \beta) = \int_{\beta}^{\infty} x e^{-\frac{x^2 + \alpha^2}{2}} I_0(\alpha x) dx. \tag{12}$$

By applying change of variables and using the Marcum Q-function definition, (10) becomes

$$P_{e1} = 1 - \sum_{n=0}^{M-1} G_1 \frac{(-1)^n}{n+1} \binom{M-1}{n} e^{-\frac{n}{n+1}\alpha^2|h|^2} \tag{13}$$

where

$$G_1 = Q_1\left(\sqrt{\frac{2}{n+1}} \alpha |h|, \sqrt{2(n+1)T_h} \right). \tag{14}$$

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When s_0 is transmitted, correct detection occurs if $R_k < T_h$ $\forall k$, and hence

$$\begin{aligned} P_{e0} &= 1 - P_{c0} \\ &= 1 - P(R_1 < T_h, , \dots, R_M < T_h | s_0) \\ &= 1 - \left(\int_0^{T_h} e^{-x} dx \right)^M \\ &= 1 - (1 - e^{-T_h})^M. \end{aligned} \tag{15}$$

The probability of error for OOFSK modulation with energy detection is

$$P_e = v P_{e1} + (1 - v) P_{e0}. \tag{16}$$

The average probability of error is then obtained from

$$\begin{aligned} \bar{P}_e &= \int_0^\infty P_e \, f(|h|) \, d|h| \\ &= \int_0^\infty P_e \frac{2|h|}{\gamma^2} e^{-\frac{|h|^2 + |d|^2}{\gamma^2}} I_0 \left(\frac{2|d||h|}{\gamma^2} \right) d|h|. \end{aligned} \tag{17}$$

When $v = 1$, OOFSK signaling reduces to ordinary FSK. In this case, (9) becomes:

$$\frac{1}{M} e^{-\alpha^2 |h|^2} I_0 (2 \sqrt{R_k \alpha^2 |h|^2}) > 0. \tag{18}$$

It is easily seen that (18) is always satisfied. So, (8) is enough for the detection of FSK signaling. Now, assuming signal s_1 is transmitted, the probability of error is:

$$\begin{aligned} P_e &= 1 - P(R_2 < R_1, \dots, R_M < R_1 | s_1) \\ &= 1 - \int_0^\infty P(R_2 < R_1, \dots, R_M < R_1 | R_1 = x) f_{R_1|s_1}(x|s_1) dx \\ &= -\sum_{n=1}^{M-1} (-1)^n \binom{M-1}{n} \frac{1}{n+1} e^{-\frac{n}{n+1} \alpha^2 |h|^2}. \end{aligned} \tag{19}$$

Due to the symmetry of the channel, when signals other than s_1 are transmitted, we have the same probability of error. Hence, (19) is the probability of error for FSK with $|h|$ known to the receiver. Note that since $Q_1(\cdot, 0) = 1$, if we choose $T_h = 0$, (13) becomes equal to (19). We obtain the average probability of error $\bar{P}_e$:

$$\begin{aligned} \bar{P}_e &= \int_0^\infty P_e f_{|h|^2}(x) dx \\ &= \int_0^\infty P_e \frac{1}{\gamma^2} e^{-\frac{|d|^2 + x}{\gamma^2}} I_0 \left(\frac{2|d|\sqrt{x}}{\gamma^2} \right) dx \\ &= -\sum_{n=1}^{M-1} (-1)^n \binom{M-1}{n} \frac{1}{(n+1)\gamma^2} e^{-\frac{|d|^2}{\gamma^2}} \\ &\quad \times \int_0^\infty e^{-\frac{n \alpha^2 x}{n+1}} e^{-\frac{x}{\gamma^2}} I_0 \left(\frac{2|d|\sqrt{x}}{\gamma^2} \right) dx. \end{aligned} \tag{20}$$

Figure 1 plots the numerical results for the probability of error of FSK and OOFSK signaling with different values of duty cycle v over the Rician channel when channel information is known to the receiver side. It shows that in the low SNR regime, OOFSK with smaller duty cycle achieves lower probability of error or for a fixed value of error probability, OOFSK signaling with lower duty cycle requires lower SNR, rendering this modulation more energy efficient.

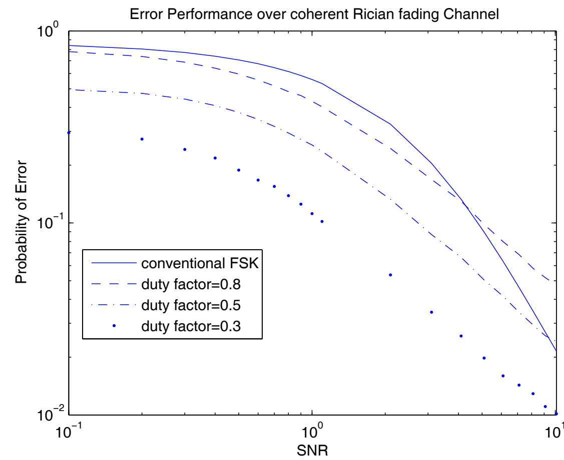

Fig. 1. Probability of error of 8-OOFSK over Rician channel with Rician factor K $= \frac{|d|^2}{\gamma^2} = 1$ when channel information is known to the receiver. Error curves are plotted for duty factor of $v = 1, 0.8, 0.5$ *and* 0.3.

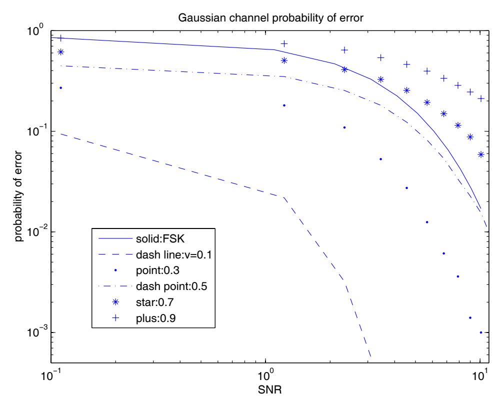

Fig. 2. Probability of error of 8-OOFSK as a function of the SNR over the unfaded Gaussian channel.

Setting $h = 1$ in (6), (8), (9) and (10), we get the joint distribution function, decision rules and probability of error for OOFSK signaling over the unfaded Gaussian channel. The probability of error of FSK signaling over the Gaussian channel [5] is:

$$P_e = \sum_{n=1}^{M-1} (-1)^{n+1} \binom{M-1}{n} \frac{1}{n+1} e^{-\frac{n\rho}{n+1}}. \tag{21}$$

where ρ is the SNR/symbol.

Fig. 2 is the comparison of FSK and OOFSK in the unfaded Gaussian channel. Similarly, we observe that decreasing the duty cycle, v, improves the energy efficiency.

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IV. OOFSK PERFORMANCE OVER NONCOHERENT RICIAN FADING CHANNELS

In noncoherent Rician fading channels, h in (2) is a circularly symmetric Gaussian random variable with mean value d and variance γ^2 and neither the transmitter nor the receiver knows the fading coefficients. Based on these assumptions, if $s_k(t)$ is transmitted, we have

$$E\{Y_m\} = \begin{cases} \alpha d e^{j\theta_m} & m = k \\ 0 & m \neq k \end{cases}, \tag{22}$$

$$var\{Y_m\} = \begin{cases} \alpha^2\gamma^2 + 1 & m = k \\ 1 & m \neq k \end{cases}. \tag{23}$$

Since Y_m is a complex Gaussian random variable, $R_m = |Y_m|^2$ is chi-square distributed and the joint distribution function of output conditioned on $s_k(t)$ being transmitted is

$$f_{\mathbf{R}|s_k}(\mathbf{R}|s_k) = \begin{cases} e^{-\sum_{j=1, j\neq k}^{M} R_j} \frac{e^{-\frac{R_k+\alpha^2|d|^2}{1+\alpha^2\gamma^2}}}{1+\alpha^2\gamma^2} I_0\left(\frac{2\sqrt{R_k\alpha^2|d|^2}}{1+\alpha^2\gamma^2}\right) & 1 \leq k \leq M \\ e^{-\sum_{j=1}^{M} R_j}, & k = 0. \end{cases}$$

Using the MAP decision criterion, we reach to the following detection rule: $s_k(t)$ ($k \neq 0$) is the detected signal if

$$f(\mathbf{R}|s_k) > f(\mathbf{R}|s_l) \Longrightarrow R_k > R_l \quad \forall l \neq k, \tag{24}$$

and

$$\frac{v}{M} f(\mathbf{R}|s_k) > (1-v) f(\mathbf{R}|s_0) \Longrightarrow R_k > \Phi^{-1}(T) \tag{25}$$

where

$$\Phi(R) = e^{\frac{\alpha^2\gamma^2 R}{1+\alpha^2\gamma^2}} I_0\left(\frac{2\sqrt{R\,\alpha^2|d|^2}}{1+\alpha^2\gamma^2}\right) \tag{26}$$

and

$$T = \frac{M(1-v)}{v}(1+\alpha^2\gamma^2)\, e^{\frac{\alpha^2|d|^2}{1+\alpha^2\gamma^2}}. \tag{27}$$

Note that (24) and (25) follow from the fact that Φ is a monotonically increasing function of R and hence the functional inverse Φ^{-1} is well-defined. In FSK signaling, the detection rule simplifies to $R_k > R_l, \forall l \neq k$, and the probability of error is readily found as

$$P_e = 1 - \int_0^\infty p_{R_k}(x)\left[\int_0^x p_{R_m}(y)dy\right]^{M-1} dx \tag{28}$$

$$= \sum_{n=1}^{M-1} (-1)^{n+1} \binom{M-1}{n} \frac{1}{n+1+n\alpha^2\gamma^2} e^{-\frac{n\alpha^2|d|^2}{n+1+n\alpha^2\gamma^2}}. \tag{29}$$

Note that although we do not have a closed form expression for Φ^{-1}, we can find threshold value through numerical methods from the equation $T_h = \Phi^{-1}(T)$. For simplicity, s_1 is assumed to be transmitted, then, the probability of error P_{e1} is:

$$\begin{aligned} P_{e1} &= 1 - P_{c1} \\ &= 1 - P\left(R_2 < R_1, \ldots, R_M < R_1, R_1 > T_h | s_1\right) \\ &= 1 - \sum_{n=0}^{M-1} (-1)^n \binom{M-1}{n} \\ &\quad \times \int_{T_h}^\infty \frac{1}{1+\alpha^2\gamma^2} e^{-\frac{[n(1+\alpha^2\gamma^2)+1]x+\alpha^2|d|^2}{1+\alpha^2\gamma^2}} I_0\left(\frac{2\alpha|d|\sqrt{x}}{1+\alpha^2\gamma^2}\right) dx. \end{aligned} \tag{30}$$

After some manipulations on the equation, the probability of error is represented in terms of the Marcum Q-function.

$$\begin{aligned} P_{e1} &= 1 - \sum_{n=0}^{M-1} (-1)^n \frac{1}{n(1+\alpha^2\gamma^2)+1} \binom{M-1}{n} e^{-\frac{n\alpha^2|d|^2}{(n(1+\alpha^2\gamma^2)+1)}} \\ &\quad \times \int_{[n(1+\alpha^2\gamma^2)+1]T_h}^\infty \frac{1}{1+\alpha^2\gamma^2} e^{-\frac{\dot{x}+\alpha^2|d|^2}{1+\alpha^2\gamma^2}} I_0\left(\frac{2\alpha|d|\sqrt{\dot{x}}}{1+\alpha^2\gamma^2}\right) d\dot{x} \\ &= 1 - \sum_{n=0}^{M-1} (-1)^n \frac{1}{n(1+\alpha^2\gamma^2)+1} \binom{M-1}{n} e^{-\frac{n\alpha^2|d|^2}{n(1+\alpha^2\gamma^2)+1}} \\ &\quad \times Q_1\left(\sqrt{\frac{2\alpha^2|d|^2}{(1+\alpha^2\gamma^2)[n(1+\alpha^2\gamma^2)+1]}}, \sqrt{\frac{2[n(1+\alpha^2\gamma^2)+1]T_h}{(1+\alpha^2\gamma^2)}}\right). \end{aligned} \tag{31}$$

When no signal is transmitted, the probability of error is:

$$\begin{aligned} P_{e0} &= 1 - P_{c0} \\ &= 1 - P\left(R_1 < T_h, \ldots, R_M < T_h \,|s_0\right) \\ &= 1 - \left(\int_0^{T_h} e^{-x} dx\right)^M \\ &= 1 - \left(1 - e^{-T_h}\right)^M. \end{aligned} \tag{32}$$

Then, the overall probability of error for OOFSK signaling over noncoherent Rician channel is:

$$P_e = vP_{e1} + (1-v)P_{e0} \tag{33}$$

Fig. 3 is the numerical result which shows that the energy efficiency improves as one operates with lower duty cycle v. Fig. 4 plots the simulated error probabilities and upper bounds for OOFSK modulation with $v = 0.2$ and 0.8 when a suboptimum threshold value of $T_h = \text{SNR}/(\nu c)$ is used where c is a parameter chosen to get the tightest upper bound.

Note that Marcum Q function has the following bounds when $\beta > \alpha > 0$: [12]

$$\frac{\beta}{\beta+\alpha} e^{-\frac{(\beta+\alpha)^2}{2}} \leq Q_1(\alpha, \beta) \leq \frac{\beta}{\beta-\alpha} e^{-\frac{(\beta-\alpha)^2}{2}}. \tag{34}$$

In (31), when $\frac{\beta}{\alpha} = \sqrt{\frac{[n(1+\alpha^2\gamma^2)+1]^2}{c|d|^2}} > 1$, using the above bounds, we can obtain bounds expressed with exponential functions rather than the Marcum Q-functions.

When $d = 0$, we obtain the Rayleigh fading channel. Now,

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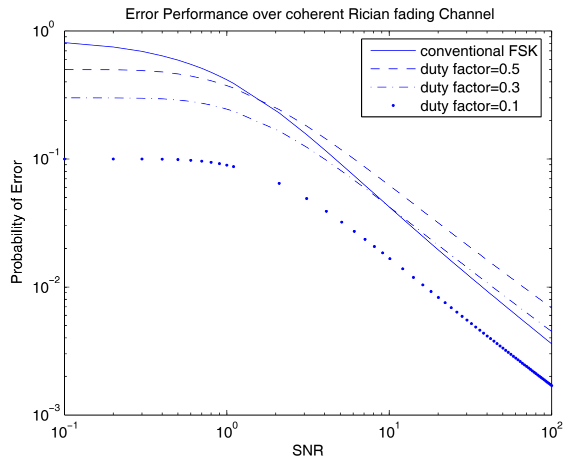

Fig. 3. Probability of error of 8-OOFSK over Rician fading channel when channel information is unknown to the receiver . The plots are for duty factor:$v = 1, 0.8, 0.5$ *and* 0.3

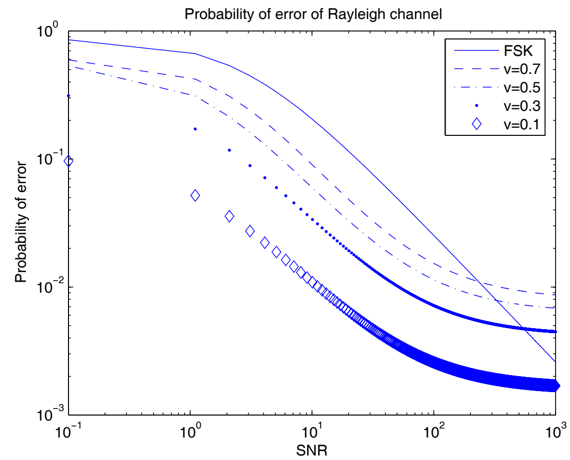

Fig. 5. Error probability of 8-OOFSK over Rayleigh Channel when channel information is unknown to receiver

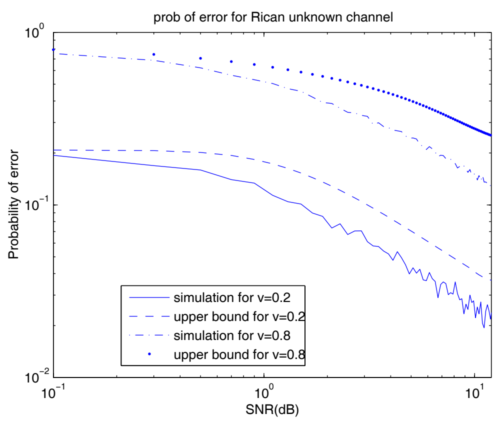

Fig. 4. Comparison of the simulation results and upper bounds for the error probability curves over the Rician unknown channel

the joint conditional *pdf* of the output energies is

$$f(\mathbf{R}|s_k)=\begin{cases} e^{-\sum_{j=1,j\neq k}^{M} R_j}\frac{1}{1+\alpha^2\gamma^2}e^{-\frac{R_k}{1+\alpha^2\gamma^2}}, k=1,2,\ldots,M \\ e^{-\sum_{j=1}^{M} R_j}, \quad k=0. \end{cases} \tag{35}$$

For Rayleigh fading channels, the MAP detector concludes that $s_k(t)$ $(k \neq 0)$ is the detected signal if

$$f(\mathbf{R}|s_k)>f(\mathbf{R}|s_l) \Longrightarrow R_k > R_l \quad \forall l \neq k \tag{36}$$

and,

$$\frac{v}{M} f(\mathbf{R}|s_k) > (1-v) f(\mathbf{R}|s_0) \Longrightarrow R_k > T_0 \tag{37}$$

where $T_0 = \frac{1+\alpha^2\gamma^2}{\alpha^2\gamma^2} \ln\left((1+\alpha^2\gamma^2)\frac{(1-v)M}{v}\right)$.

Similarly as before, if we assume without loss of generality that $s_1(t)$ is transmitted, the probability of error is

$$P_{e1} = 1 - \int_{T_0}^{\infty} P(R_2 < x, \ldots, R_M < x | R_1 = x) p_{R_1}(x)\, dx$$
$$= 1 - \sum_{n=0}^{M-1} (-1)^n \binom{M-1}{n} \frac{1}{n(1+\alpha^2\gamma^2)+1} e^{-\frac{[n(1+\alpha^2\gamma^2)+1]T_0}{1+\alpha^2\gamma^2}}$$

If s_0 is sent, the probability of error is

$$P_{e0} = 1 - \left(1 - e^{-T_0}\right)^M. \tag{38}$$

The overall probability of error is given by

$$P_e = vP_{e1} + (1-v)P_{e0}. \tag{39}$$

Fig. 5 plots the error probability curves achieved by FSK and OOFSK modulations with different values of duty cycle v over noncoherent Rayleigh channels. Fig. 6 shows that the smaller the duty factor is, the more energy the OOFSK signaling saves.

V. Conclusion

We have analyzed the error performance of OOFSK signaling over coherent and noncoherent fading channels. Assuming that MAP detection is employed at the receiver, we have obtained expressions for the probability of error. Simulation and numerical results show that energy efficiency is improved considerably by choosing smaller duty factor for both coherent and noncoherent fading channels

References

[1] A. Ephremides, "Energy concerns in wireless networks," *IEEE Wireless Commun.*, vol. 9, pp. 48-59, August 2002.

[2] A. J. Goldsmith and S. B. Wicker, "Design challenges for energy-constrained ad hoc wireless networks," *IEEE Wireless Commun.*, vol. 9, pp. 8-27, August 2002.

[3] A. Y. Wang, S. Cho, C. G. Sodini, and A. P. Chandrakasan, "Energy efficient modulation and MAC for asymmetric RF microsensor systems," *Proc. Int. Symp. Low Power Electronics and Design*, pp. 106-111, 6-7 August 2001.

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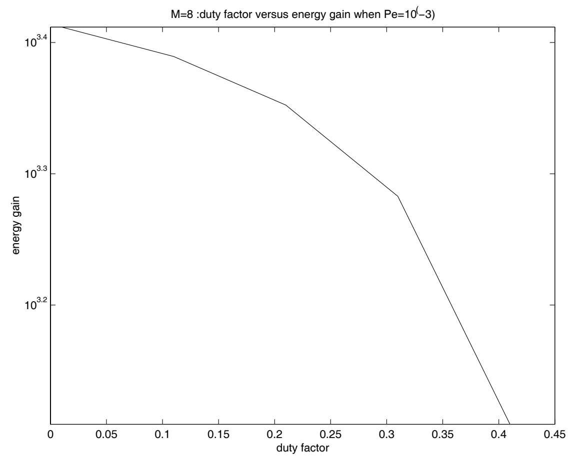

Fig. 6. Energy saving for different duty factor values v when $P_e = 10^{-3}$.

[4] S. Shakkottai, T.S. Rappaport and P.C. Karlsson, "Cross-layer design for wireless networks," *IEEE Communications Magazine*, vol. 41 , pp. 74-80, Oct 2003.

[5] J. G. Proakis and M. Salehi, *Communication Systems Engineering*, Prentice Hall, 2001

[6] R. G. Gallager, *Information Theory and Reliable Communication.* Wiley: New York, 1968

[7] W. E. Stark, "Capacity and Cutoff Rate of Noncoherent FSK with Nonselective Rician Fading," *IEEE Transaction on Communications*, vol.COM 33, NO.11, Nov. 1985.

[8] W. C. Lindsey, "Error Probability for Rician Fading Multichannel Reception of Binary and N-ary Signals", 1964.

[9] C. Luo, M. Medard, and L. Zheng, "Error Exponens for Multi-tone Frequency Shift Keying on Wideband Rayleigh Fading Channels", Globecom 2003, Dec,2003.

[10] S. Cui, A. J.Goldensmith, and A. Bahai, "Energy-constrained Modulation Optimization", *IEEE Transaction on Wireless Communicatios, Sep, 2005*

[11] M. C. Gursoy, H. V. Poor, S. Verdú, "On-Off frequency-shift keying for wideband fading channels" to appear in the *EURASIP Journal on Wireless Communications and Networking*, 2006.

[12] M. K. Simon and M.-S. Alouni, "A unified approach to the performance analysis of digital communication over generalized fading channels", *Proc. of the IEEE*, vol. 86, no. 9, pp. 1860-1877, Sept. 1998

[13] E. Shih ,S. H. Cho, "Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks",*International Conference on Mobile Computing and Networking, Proceedings of the 7th annual international conference on Mobile computing and networking*, pp. 272 - 287, Rome, Italy, 2001.

[14] T.V.Dam, K. Langendon, "An adaptive energy-efficient MAC protocol for Wireless Sensor Network" *The First ACM Conference on Embeded Networked Sensor Systems (Sensys 03')* , Los Angeles, CA, USA, November, 2003.

[15] G. Lu, B. Kris., C. S. Rag., "An adaptive energy-efficient and low-latency MAC for Data Gathering in Wireless Sensor Networks" , *Procedings of the 18th International Paralevel and Distributed Processing Symposium, (IPDPS 04')*, 2004.

[16] K. Jamieson, H. Bala, "Sift:A MAC Protocol for Event-Driven Wireless Sensor Networks",*MIT Laboratory for Computor Science, Tech*, Rep. 894, May 2003.

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