Chung EURASIP Journal on Wireless Communications and Networking 2012, **2012**:190
http://jwcn.eurasipjournals.com/content/2012/1/190

EURASIP Journal on
Wireless Communications and Networking
a SpringerOpen Journal

RESEARCH **Open Access**

An analytical expression for the BER of optimal single user detection of a BPSK signal contaminated by multiple CCIs

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Abstract

We derive an analytical expression for the bit-error rate (BER) of optimal single user detection of a binary phase-shift keying signal corrupted by multiple cochannel interferers. The channel capacity is also calculated to investigate the BER performance.

Keywords: multiple cochannel interference, channel capacity, error probability, maximum likelihood detection

1. Introduction

The problem of detecting a binary phase-shift keying (BPSK) signal corrupted by a single cochannel interferer (SCI) and additive white Gaussian noise (AWGN) has been investigated [1-11]. In [1], a suboptimal receiver is derived that utilizes the carrier frequency difference. In [2], an optimal BPSK receiver is derived assuming Rayleigh fading and no receiver knowledge of signal parameters. In [3], a suboptimal BPSK receiver structure is proposed for a non-faded channel. In [4], the optimum receiver is derived for a two-user synchronous BPSK channel. The bit-error rate (BER) performance of the optimum receiver was compared with that of the conventional matched-filter receiver in [4] and the jointly optimal receiver (JOR) in [5]. The exact probability of error of an SCI-JOR was first obtained in [6,7]. An exact expression for the BER of an individually optimal receiver (IOR) used to detect a BPSK signal corrupted by a similar SCI and AWGN was derived in [10]. When a BPSK signal corrupted by an SCI and AWGN is detected, the IOR is the optimal multiuser detector [8]. The JOR is also analyzed in [9]. On the other hand, the optimal single user detection (OSUD) in an SCI and AWGN is investigated and the BER of the OSUD is calculated in [11]. However, the number of cochannel interferers (CCIs) can increase for multiuser communications such as cellular mobile systems, in which the domain degradation is the interference due to other users communicating on the same channel, as the number of users increases. In this article, we propose the OSUD for a BPSK signal detection in the presence of AWGN and multiple cochannel interferers (MCIs). In addition, while in [11], the real roots were obtained by the equation of the product tanh functions, we solve the equation specifically, which is obtained by equating log-likelihood ratios (LLRs) with zero. The channel capacity is also calculated to investigate the BER performance.

2. Signal model and MCI-OSUD derivation

We consider an MCI model. Assume that the baseband received signal is given by

$$r(t) = A_0 b_0 s_0(t) + \sum_{i=1}^{N_I} A_i b_i s_i(t) + n(t) \tag{1}$$

where b_i, A_i, and $s_i(t)$, $i = 0, 1,\ldots,N_I$, are the information bit, amplitude, and signal waveform of the ith user, respectively, the number of interferers is N_I, $n(t)$ is an AWGN noise with zero mean and double-sided power spectral density $\sigma^2 = N_0/2$, and $A_0 b_0 s_0(t)$ is the desired user's transmitted signal. The cross correlations are defined as $\rho_i \triangleq \int_0^T s_0(t)s_i(t)dt$, $i = 0, 1,\ldots,N_I$, where T is the symbol duration. Similar to [10], we assume zero timing error, zero intersymbol interference (ISI), and unit energy for signals. Then, the sampled output of the receiver filter matched to $s_0(t)$ is given by

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$$r_0 = b_0A_0 + \sum_{i=1}^{N_I} b_iA_i\rho_i + n_0 = b_0A_0 + \sum_{i=1}^{N_I} b_iI_i + n_0 \qquad (2)$$

where $I_i = A_i\rho_i$, $i = 0, 1,...,N_I$, and n_0 is the component of $n(t)$ along $s_0(t)$, which is also a Gaussian random variable (RV) with zero mean and variance $\sigma^2 = N_0/2$. Now, we consider the observation noise which is defined as $w \triangleq \sum_{i=1}^{N_I} b_iI_i + n_0$. If binary bits are transmitted with equal probability and independent of each other and also independent of the RV n_0, then the probability density function (PDF) of w can be calculated as follows

$$f_W(w) = \frac{1}{2^{N_I}} \sum_{d=0}^{2^{N_I}-1} \mathcal{N}\left(w + \sum_{i=1}^{N_I} (-1)^{d_{(2)}(N_I+1-i)} I_i\right), \qquad (3)$$

where $d_{(2)}(k)$ is defined as the kth bit in the binary representation of an integer d, i.e.,

$$d \triangleq \sum_{k=1}^{N_I} d_{(2)}(k)2^{k-1} \triangleq \left(d_{(2)}(N_I)\cdots d_{(2)}(2)d_{(2)}(1)\right)_{\{2,N_I\}}, \qquad (4)$$

$(\bullet)_{\{2,N_I\}}$ denotes a binary number with N_I bits, $d_{(2)}(k) \in \{0, 1\}$, $\mathcal{N}(x)$ is given by $\exp(-x^2/N_0)/\sqrt{\pi N_0}$. The optimum decision for the desired user's information bit can be obtained from the following hypothesis testing problem,

$$H_1 : r_0 = A_0 + w, \qquad H_0 : r_0 = -A_0 + w. \qquad (5)$$

Using LLRs, the binary decision is given by

$$\hat{b}_0 = \text{sgn}\,(\Lambda(r_0)) = \text{sgn}\left(\log\frac{f_{R_0}(r_0|H_1)}{f_{R_0}(r_0|H_0)}\right) \qquad (6)$$

where the LLR $\Lambda(r_0)$ is defined as $\log\left(f_{R_0}(r_0|H_1)/f_{R_0}(r_0|H_0)\right)$ and sgn$(\cdot)$ denotes signum function. Substituting (3) in (5) and after some algebraic manipulation, the OSUD in the presence of AWGN and MCIs is given by

$$\hat{b}_0 = \text{sgn}\left[\frac{4A_0}{N_0}r_0 - \Omega(r_0)\right] \qquad (7)$$

where $\Omega(r_0)$ is defined as

$$\Omega(r_0) = \log\frac{\sum_{d=0}^{2^{N_I-1}-1}\left\{e^{-\frac{2}{N_0}\left(+\sum_{i=1}^{N_I}\sum_{\substack{k=1\\k>i}}^{N_I}(-1)^{d_{(2)}(N_I+1-i)}(-1)^{d_{(2)}(N_I+1-k)}I_iI_k\right)}\cosh\left[\frac{2}{N_0}(r_0+A_0)\left(\sum_{i=1}^{N_I}(-1)^{d_{(2)}(N_I+1-i)}I_i\right)\right]\right\}}{\sum_{d=0}^{2^{N_I-1}-1}\left\{e^{-\frac{2}{N_0}\left(+\sum_{i=1}^{N_I}\sum_{\substack{k=1\\k>i}}^{N_I}(-1)^{d_{(2)}(N_I+1-i)}(-1)^{d_{(2)}(N_I+1-k)}I_iI_k\right)}\cosh\left[\frac{2}{N_0}(r_0-A_0)\left(\sum_{i=1}^{N_I}(-1)^{d_{(2)}(N_I+1-i)}I_i\right)\right]\right\}} \qquad (8)$$

It is easy to show that the MCI-OSUD of (7) simplifies to the SCI-OSUD in [4] for $I_1 \neq 0$ and $I_k = 0$, $k = 2, 3,..., N_I$.

3. BER derivation and channel capacity calculation

In order to evaluate the BER, we need to find the intervals for $\Lambda(r_0) > 0$ or $\Lambda(r_0) < 0$. We observe that the numerator and the denominator of the argument of the logarithm in $\Lambda(r_0)$ are the sums of the bell-shaped curves, respectively. The centers of bell curves are numbered as

$$\begin{aligned} d+1 &\triangleq \mu\left(A_0 - \sum_{i=1}^{N_I}(-1)^{d_{(2)}(N_I+1-i)}I_i\right), \\ -c-1 &\triangleq \mu\left(-A_0 + \sum_{i=1}^{N_I}(-1)^{c_{(2)}(N_I+1-i)}I_i\right), \end{aligned} \qquad (9)$$

where $d,c = 0,1,\ldots,2^{N_I}-1$. Since $\Lambda(r_0)$ is an odd function, the equation of $\Lambda(r_0) = 0$ always has a real root $r_0 = 0$. It is very difficult to obtain the exact real roots except a real root $r_0 = 0$. Therefore, we use the Jacobian logarithm to obtain the approximate real roots as follows,

$$\begin{aligned} \log(e^x + e^y) &= \max(x,y) + \log(1 + e^{-|y-x|}) \\ &\approx \max(x,y). \end{aligned} \qquad (10)$$

Then $\Lambda(r_0) = 0$can be written as

$$\min_d \left|r_0 - \mu^{-1}(d+1)\right| \approx \min_c \left|r_0 - \mu^{-1}(-c-1)\right|, \qquad (11)$$

where $d,c = 0,1,\ldots,2^{N_I}-1$. In order to solve (11), we have the case C_i, $1 \le i \le N_c$, which is a set of marginal conditions, where N_c is the number of cases. Then the set R_i of real roots corresponding to C_i can be obtained by solving (11). We order $2N_r^{(i)}+1$ real roots $p_j(i) \in R_i$, $j = -N_r^{(i)}, -N_r^{(i)}+1, \ldots, -1,0,1,\ldots,N_r^{(i)}-1,N_r^{(i)}$, as follows,

$$p_{N_r^{(i)}}(i) > p_{N_r^{(i)}-1}(i) > \cdots > p_1(i) > p_0(i) = 0 > p_{-1}(i) = -p_1(i) > \cdots > p_{-N_r^{(i)}}(i) = -p_{N_r^{(i)}}(i). \qquad (12)$$

Then, given the case C_i, the decision intervals for $\Lambda(r_0) > 0$ are given by

$$\begin{array}{ccccc} p_{N_r^{(i)}}(i) & < & r_0 & & \\ p_{N_r^{(i)}-2}(i) & < & r_0 & < & p_{N_r^{(i)}-1}(i) \\ & & \vdots & & \\ -p_{N_r^{(i)}-2}(i) & < & r_0 & < & -p_{N_r^{(i)}-3}(i) \\ -p_{N_r^{(i)}}(i) & < & r_0 & < & -p_{N_r^{(i)}-1}(i) \end{array} \qquad (13)$$

For the case C_1, the BER $P_b^{(1)}$ is calculated as follows

$$P_b^{(1)} = \frac{1}{2^{N_I}} \sum_{d=0}^{2^{N_I}-1} Q\left(\frac{\mu^{-1}(d+1)}{\sqrt{N_0/2}}\right). \qquad (14)$$

For the case C_i, $2 \le i \le N_c$, and the center -c-1, $-2^{N_I} \le -c-1 \le -1$, we can obtain the following condition

$$p_{j-2}(i) < p_{j-1}(i) < \mu^{-1}(-c-1) < p_j(i) < p_{j+1}(i). \tag{15}$$

Then the conditional BER is calculated as follows

$$P_{-c-1}^{(i)} \approx \sum_{h=0}^{N_r^{(i)}-j} \frac{(-1)^h}{2^{N_I}} Q\left(\frac{p_{j+h}(i)-\mu^{-1}(-c-1)}{\sqrt{N_0/2}}\right) + \sum_{h=0}^{N_r^{(i)}+j-1} \frac{(-1)^h}{2^{N_I}} Q\left(\frac{\mu^{-1}(-c-1)-p_{j-1-h}(i)}{\sqrt{N_0/2}}\right), \tag{16}$$

where $Q(x) = \int_x^\infty (1/\sqrt{2\pi})\exp(-t^2/2)dt$. Then the BER $P_b^{(i)}$ is calculated as follows

$$P_b^{(i)} \approx \sum_{c=0}^{2^{N_I}-1} P_{-c-1}^{(i)} \quad , \tag{17}$$

where $2 \le i \le N_c$.

3.1. BER derivation for $N_I = 2$

We continue our derivation for $N_I = 2$ and without loss of generality, we assume $I_1 \ge I_2$. Then we can obtain the real roots solving (11) as follows

$$\begin{array}{ll} 0 & \textit{for } A_0 > I_1 + I_2, \\ 0, \pm I_2 & \textit{for } A_0 < I_1 + I_2, A_0 > I_1, \\ 0, \pm I_2, \pm I_1 & \textit{for } A_0 > I_1 - I_2, I_1 > A_0 > I_2, \\ 0, \pm I_1 & \textit{for } A_0 < I_1 - I_2, I_1 > A_0 > I_2, \\ 0, \pm I_1, \pm(I_1+I_2) & \textit{for } A_0 > I_1 - I_2, I_1 > I_2 > A_0, \\ 0, \pm I_1, \pm(I_1+I_2), \pm(I_1-I_2) & \textit{for } A_0 < I_1 - I_2, I_1 > I_2 > A_0. \end{array} \tag{18}$$

Then, the BER can be calculated by (14) or (17).

2",1,0,1,0,0pc,0pc,0pc,0pc>3.2. BER derivation for $N_I > 2$

Next, we continue the derivation for $N_I > 2$, which is more complicated than the previous case because the number N_c of cases increases rapidly. To make the problem tractable, we assume the following condition

$$A_0 > I_1 > 2I_2 > \cdots > 2^{N_I-1} I_{N_I} > 0. \tag{19}$$

In the above condition, a practical situation, in which the interference of the CCIs is not severe, can be assumed. Then the possible marginal conditions for various real roots are given by

$$\begin{aligned} &\mu^{-1}(-c-1) - \mu^{-1}(d+1) < 0, \\ &-\mu^{-1}(-c-1) + \mu^{-1}(d+1) < 0, \end{aligned} \tag{20}$$

where $d,c = 0,1,\ldots,2^{N_I}-1$. These conditions can be written as greatly simple forms with ternary numbers, which are

$$t \triangleq \sum_{k=1}^{N_I} t_{(3)}(k) 3^{k-1} \triangleq \left(t_{(3)}(N_I)\cdots t_{(3)}(2) t_{(3)}(1)\right)_{\{3,N_I\}}, \tag{21}$$

where $(\bullet)_{\{3,N_I\}}$ denotes a ternary number with N_I digits, and $t_{(3)}(k) \in \{0, 1, 2\}$ is defined as the kth digit in the ternary representation of an integer t. The left-hand sides in (20) are numbered as

$$\begin{aligned} 3^{N_I} - t &\triangleq \lambda\left(A_0 - \sum_{i=1}^{N_I}\left(t_{(3)}(N_I+1-i) - 1\right) I_i\right), \\ -3^{N_I} + t &\triangleq \lambda\left(-A_0 + \sum_{i=1}^{N_I}\left(t_{(3)}(N_I+1-i) - 1\right) I_i\right), \end{aligned} \tag{22}$$

where $t = 0, 1, \ldots, 3^{N_I}-1$. The conditions for various real roots can efficiently be represented as a table. Now, we explain the procedure to create the table. The first step is to draw a table with $(11\cdots1)_{\{3,N_I-2\}}$ rows and $(11\cdots1)_{\{3,N_I-1\}}$ columns. Fill the first row with the decimal numbers from left to right, starting with 1 and ending with $(11\cdots1)_{\{3,N_I-1\}}$. Then copy the one-cell left-shifted version of the first row into the second row, the one-cell left-shifted version of the second row into the third row, and so on. Remove the entries below the main diagonal. On the first row, find the numbers for inequalities corresponding to $\mu^{-1}(d+1) < \mu^{-1}(-c-1)$, where $d = 0, 1, \ldots, 2^{N_I-1}-1$ and $c = 0$. Write -c-1 on a new additional column, following the same pattern as d+1 with the opposite sign, where $c = 0, 1, \ldots, 2^{N_I-2}-1$. Finally, mark the entries at the intersection of -c-1 rows and d+1 columns. Figure 1 shows the procedure for generating the table with N_I = 4 interferers. The number of columns is the number of conditions for various real roots, which are numbered as 1 to $1 + (11\cdots1)_{\{3,N_I-1\}}$. Then the set C_i with $N_c = 1 + (11\cdots1)_{\{3,N_I-1\}}$ is defined as

$$C_i = \left\{\lambda^{-1}\left(-m(-c-1)\right) < 0, \lambda^{-1}\left(n(-c-1)\right) < 0 \,\middle|\, c = 0, 1, \ldots, 2^{N_I-2}-1\right\} \tag{23}$$

where m(-c-1) is the biggest and nearest marked number from i including i and n(-c-1) is the smallest and nearest marked number from i excluding i on each row -c-1, where $-2^{N_I-2} \le -c-1 \le -1$. If m does not exist, there is no corresponding marginal condition. The set D_i of candidates for real roots corresponding to the case C_i is defined as

$$\begin{aligned} D_i = \Big\{ &\pm\left(\mu^{-1}(d_{m(-c-1)}+1) - \mu^{-1}(-c-1)\right)/2, \\ &\pm\left(\mu^{-1}(-c-1) - \mu^{-1}(d_{n(-c-1)}+1)\right)/2, \\ &0 \,\Big|\, c = 0, 1, \ldots, 2^{N_I-2}-1 \Big\}, \end{aligned} \tag{24}$$

where the indexes ($d_{m(-c-1)}$+1) and ($d_{n(-c-1)}$+1) of the centers of bell curves correspond to m(-c-1) and n(-c-1) on each row -c-1, respectively. For the set E_i given by

$$E_i = \left\{(-c_1 - 1),\, (-c_2 - 1) \,\middle|\, (d_{m(-c_1-1)} + 1) = (d_{m(-c_2-1)} + 1)\,,\; c_1, c_2 = 0, 1, \ldots, 2^{N_I-2} - 1, c_1 \neq c_2 \right\}, \tag{25}$$

the updated set F_i is obtained from the set D_i by removing $\pm(\mu^{-1}(d_{m(-c-1)}+1)-\mu^{-1}(-c-1))/2$, except the biggest element $(-b-1) \in E_i$, for $(-c-1) \neq (-b-1)$, $(-c-1) \in E_i$, and the updated set R_i is obtained from the set F_i by removing $\pm\left(\mu^{-1}(-c-1) - \mu^{-1}(d_{n(-c-1)}+1)\right)/2$, except the smallest element $(-s-1) \in E_i$, for $(-c-1) \in E_i$, $(-c-1) \neq (-s-1)$.

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1	2	3	4	5	6	7	8	9	10	11	12	13	14

$\Downarrow$

1	2	3	4	5	6	7	8	9	10	11	12	13	14
2	3	4	5	6	7	8	9	10	11	12	13	14	
3	4	5	6	7	8	9	10	11	12	13	14		
4	5	6	7	8	9	10	11	12	13	14			
5	6	7	8	9	10	11	12	13	14				

$\Downarrow$

1	2	3	4	5	6	7	8	9	10	11	12	13	14
	3	4	5	6	7	8	9	10	11	12	13	14	
		5	6	7	8	9	10	11	12	13	14		
			7	8	9	10	11	12	13	14			
				9	10	11	12	13	14				

$\Downarrow$

$-c-1 \setminus d+1$	+1	+2		+3	+4					+5	+6		+7	+8
−1	1	2	3	4	5	6	7	8	9	10	11	12	13	14
−2		3	4	5	6	7	8	9	10	11	12	13	14	
			5	6	7	8	9	10	11	12	13	14		
−3				7	8	9	10	11	12	13	14			
−4					9	10	11	12	13	14				

$\Downarrow$

$-c-1 \setminus d+1$	+1	+2		+3	+4					+5	+6		+7	+8
−1	$\boxed{1}$	$\boxed{2}$	3	$\boxed{4}$	$\boxed{5}$	6	7	8	9	$\boxed{10}$	$\boxed{11}$	12	$\boxed{13}$	$\boxed{14}$
−2		$\boxed{3}$	4	$\boxed{5}$	$\boxed{6}$	7	8	9	10	$\boxed{11}$	$\boxed{12}$	13	$\boxed{14}$	
			5	6	7	8	9	10	11	12	13	14		
−3				$\boxed{7}$	$\boxed{8}$	9	10	11	12	$\boxed{13}$	$\boxed{14}$			
−4					$\boxed{9}$	10	11	12	13	$\boxed{14}$				

Figure 1 Procedure of generating a table with conditions for various real roots. The number N_I of interferers is 4.

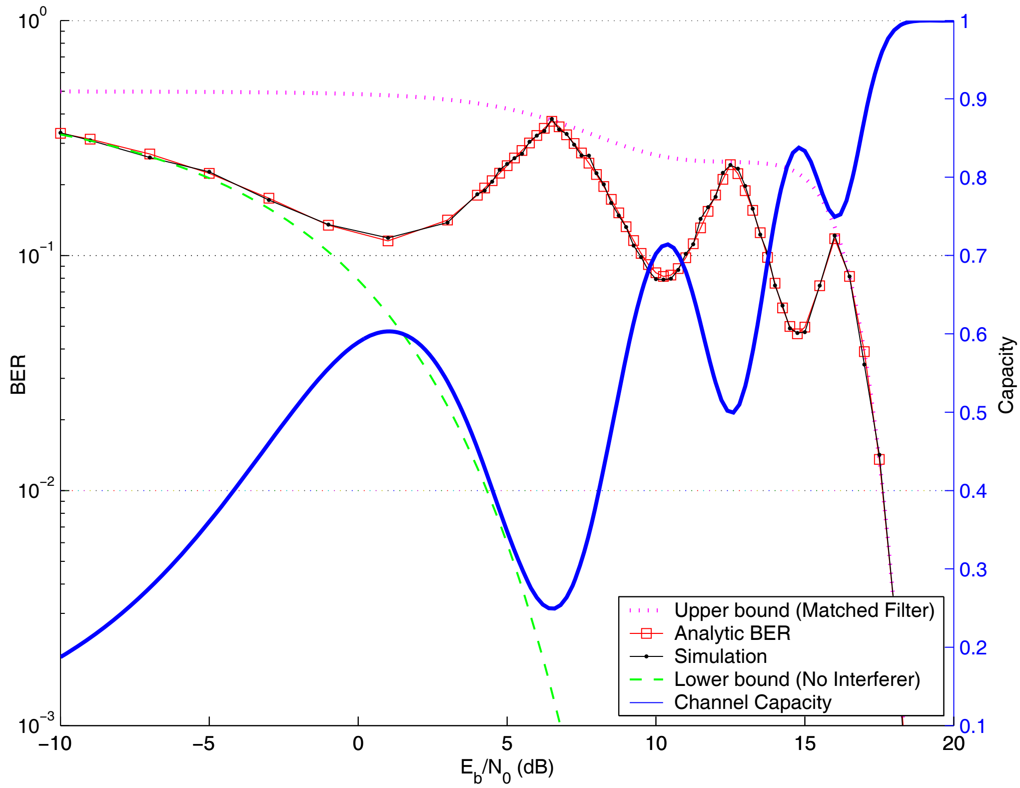

Figure 2 The left axis is the BER and the right axis is the capacity (in bit/channel use) for I_1=6.0 and I_2=3.0 with N_0=2.0.

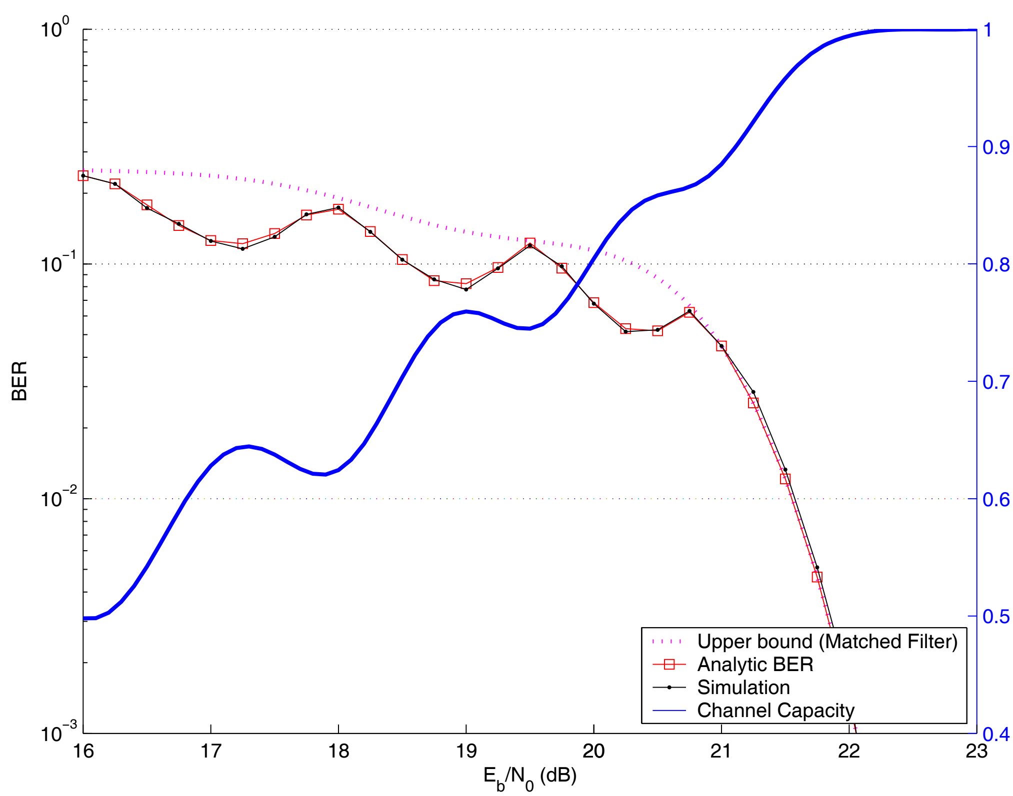

Figure 3 The left axis is the BER and the right axis is the capacity (in bit/channel use) for I_1=9.0, I_1=4.4, I_3=2.1, I_4=1.0 and with N_0=2.0.

Figure 1. Procedure of generating a table with conditions for various real roots. The number N_I of interferers is 4.

In summary, with the set C_i of marginal conditions, we obtain the set R_i of real roots corresponding to C_i by solving (11). For the case C_i, $1 \le i \le N_c$, the real roots $p_j(i) \in R_i$, $j = -N_r^{(i)}, \ldots, N_r^{(i)}$, and the center $-c-1$, $-2^{N_I} \le -c-1 \le -1$, we obtain the condition $p_{j-1}(i) < \mu^{-1}(-c-1) < p_j(i)$. Then conditional BER $P_{-c-1}^{(i)}$ is calculated by (16) and the BER $P_b^{(i)}$ is calculated by (14) or (17).

In addition, we calculate the channel capacity. We consider the channel of (4) with possible inputs A_0 or $-A_0$. The capacity of this channel in bit/channel use is given by [12]

$$C = 1 - \frac{1}{2}\int_{-\infty}^{\infty} f_{R_0}(r_0|H_1)\log_2\left(1 + e^{-\Lambda(r_0)}\right) dr_0 - \frac{1}{2}\int_{-\infty}^{\infty} f_{R_0}(r_0|H_0)\log_2\left(1 + e^{\Lambda(r_0)}\right) dr_0 \tag{26}$$

where by using (3) and (4), $f_{R_0}(r_0|H_1) = f_W(r_0 - A_0)$ and $f_{R_0}(r_0|H_0) = f_W(r_0 + A_0)$. Then the capacity is computed by (26).

4. Results

Figure 2 shows analytical BERs, simulations, and channel capacity of the proposed MCI-OSUD for $N_I = 2$. We define the signal-to-noise ratio (SNR) as $E_b/N_0 \triangleq A_0^2/N_0$. The upper bound, which is the hard decision for the outputs of the matched filter, is also shown. When there is no interferer, the BER is a lower bound. As the SNR changes, i.e., the amplitude A_0 of the desired user, the condition C_i satisfied also changes even though I_k's are fixed. The analytical BER coincides with the simulation. This validates our approximation. For the low SNR region, the BER performance of the MCI-OSUD approaches that of no interferer case. After fluctuations due to multiple interferers, the MCI-OSUD BER performance approaches that of the matched filter. The channel capacity is also in good agreement with the MCI-

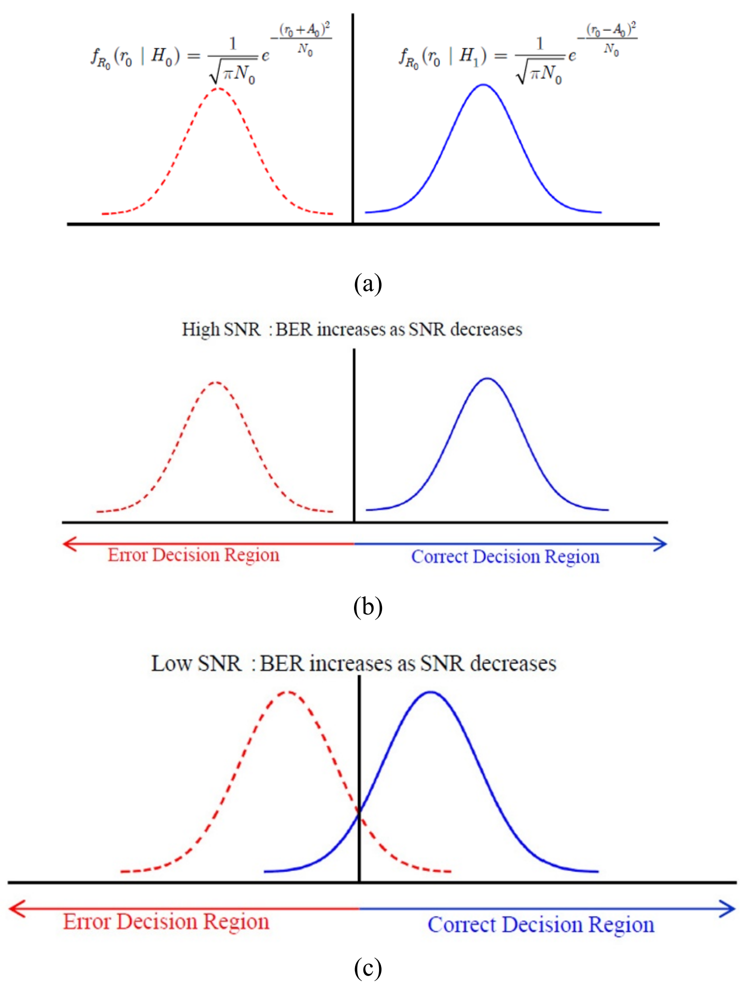

Figure 4 Illustration of no interferer case.

OSUD BER, i.e., the higher the capacity is, the lower the BER is and vice versa. We note that while analytical BERs, simulations, and the channel capacity of the SCI-OSUD in [11] have a single local minimum, those of the proposed MCI-OSUD have multiple local minima, which show the existence of multiple interferers. Similar results are obtained for $N_I = 4$, shown in Figure 3. Note that for $N_I > 2$, we assume (19). Therefore, the leftmost SNR, i.e.,

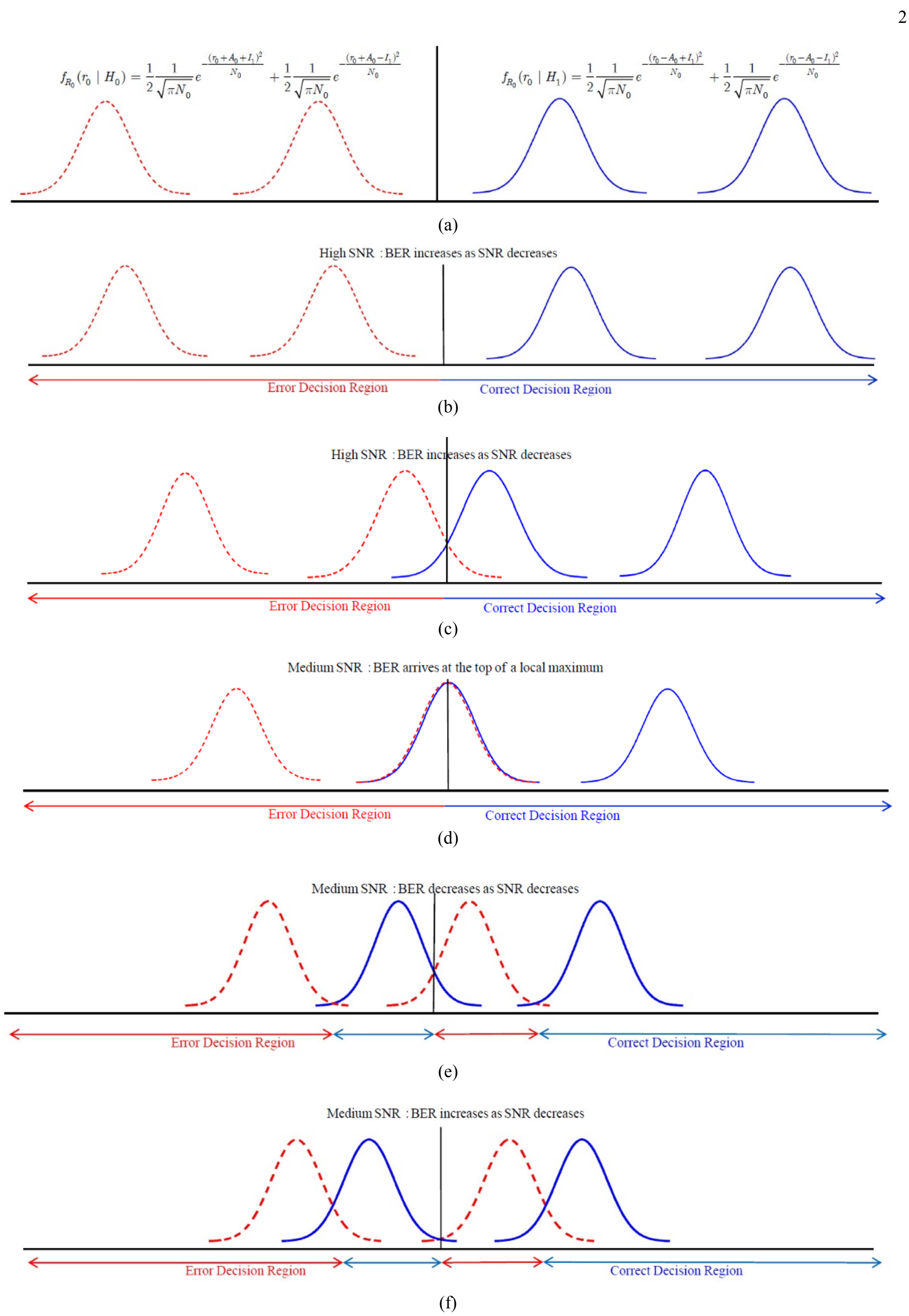

Figure 5 Illustration of a single interferer case.

16 dB, in Figure 3 is the minimum SNR, which satisfies (19). Note that the leftmost SNR is not a limitation because we can change N_0 so that the different leftmost SNR is obtained. For simulations, we used Monte Carlo simulators. Then, we averaged over 50,000 trials at each SNR. In addition, we define the maximum mismatch as the maximum value of absolute differences between the simulations and the analytical results. For the simulations in Figures 2 and 3, we obtained the maximum mismatches of 0.014 and 0.0081, respectively. Usually, the BER is non-increasing and the capacity is non-decreasing as the SNR increases. However, with CCIs, generally these are not true. This phenomenon can be explained clearly with the simplest case, i.e., a single interferer case. Before we explain a single interferer case, let us first review no interferer case. For this case, the conditional PDFs are given as in Figure 4a. Then at high SNRs, the BER increases as the SNR decreases. The decision region is shown in Figure 4b. For this case, the BER increases monotonically until the SNR reaches at the low SNR as shown in Figure 4c. However, with CCIs, generally the BER does not increase monotonically as the SNR decreases. For this case, the conditional PDFs are given in Figure 5a. Then at high SNRs, the BER increases as the SNR decreases. The decision region is shown in Figure 5b. The BER increases monotonically until the SNR reaches at some SNR as shown in Figure 5c. Then the BER arrives at the top of a local maximum shown in Figure 5d. After the BER reaches the local maximum, the BER decreases as the SNR decreases over the medium SNR region shown in Figure 5e. Then after the BER reaches the local minimum, the BER increases as the SNR decreases as usual shown in Figure 5f. As shown above, the physical interpretation is now clear. When there exists CCIs, they can interfere constructively as well as destructively. Therefore, the BER (and in turn the capacity) is not always monotonically increasing or decreasing for the cochannel interference case.

5. Conclusion

We derived an analytical expression for the BER of the MCI-OSUD. The effect of MCIs on the BER was analyzed. To investigate the BER performance, the channel capacity was also calculated. The capacity, the analytical result, and the simulation are in good agreement.

Competing interests

The author declares that they have no competing interests.

Received: 7 January 2012 Accepted: 8 June 2012 Published: 8 June 2012

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doi:10.1186/1687-1499-2012-190
Cite this article as: Chung: An analytical expression for the BER of optimal single user detection of a BPSK signal contaminated by multiple CCIs. *EURASIP Journal on Wireless Communications and Networking* 2012 **2012**:190.