JOINT PARTIAL-TIME PARTIAL-BAND JAMMING OF A MULTICARRIER DS-CDMA SYSTEM IN A FADING ENVIRONMENT

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ABSTRACT

The impact of joint partial-band, partial-time jamming on a multicarrier asynchronous DS-CDMA system in a Rayleigh fading environment is studied. Two types of partial-time jamming are studied: equal probability jamming per symbol, and burst jamming. An easy to evaluate upper bound using the Chernoff bound is provided and compared to simulation results.

Index Terms— Multicarrier, DS-CDMA, multipath fading, jamming

1. INTRODUCTION

Different realizations of multitone direct-sequence code-division multiple access (DS-CDMA) and multicarrier (MC) DS-CDMA systems have been proposed and their performances have been analyzed in many publications [1]-[8]. However, there are not many studies on the performance of MC-DS-CDMA systems under joint partial-time, partial-band jamming. Most of the previous research focus on either partial-time-only jamming or partial-band-only jamming. It is well-known that DS-CDMA systems are vulnerable to partial-time jamming ([9],[10]), and in [11], [12] it can be seen that multicarrier systems can be vulnerable to partial-band jamming. In this paper, we focus on the effect of joint partial-time, partial-band jamming on the MC-DS-CDMA system described in [1]. This system's performance under multiuser access and multipath fading channels was analyzed and compared to single carrier CDMA systems in [1], while its performance under partial-band-only jamming in a multipath fading environment was provided in [2].

The performance of CDMA systems undergoing a jamming attack has been studied extensively for the single carrier case. In [9], [13], [14], the performance of coded and uncoded single carrier DS-CDMA systems under fading and partial-time jamming was studied. A RAKE receiver was employed to exploit path diversity. The result can be adapted to MC-DS-CDMA systems with maximal-ratio combining. In [15]-[17] the performance of a MC CDMA system under full-time, partial-band jamming was studied. And in [2], the performance of MC-DS-CDMA under full-time, partial-band jamming was studied for both narrowband Gaussian noise and continuous-wave tone interference.

In [8], the performance of uncoded MC-DS-CDMA under optimized joint partial-time, partial-band jamming was studied for both AWGN channels and Rayleigh fading. There, it was assumed that the background noise is negligible compared to the jammer. As a result, full-band jamming is always optimal when maximal-ratio combining is used, since any unjammed subcarrier will dominate the test statistics due to the absence of background noise.

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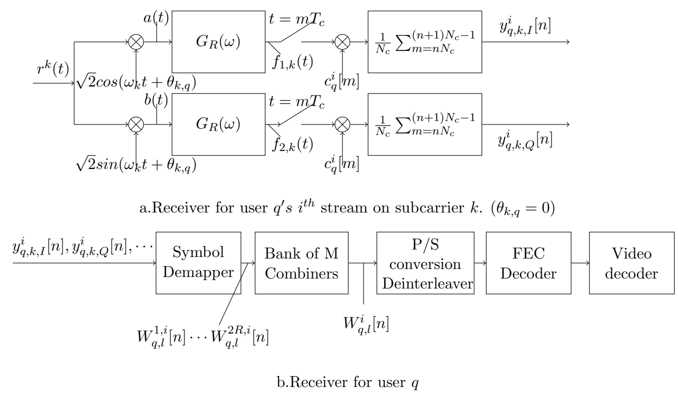

Fig. 1. Receiver for user q on subcarrier k

The goal for this paper is to study the system performance in a Rayleigh fading environment while under joint partial-time, partial-band Gaussian jamming. Unlike in [2], where partial-band jamming is considered, we do not assume knowledge of the system's mapping mechanism or which bands are being jammed. Compared to [8], we consider a coded system without ignoring thermal noise.

The system described in [1] and relevant test statistics are reviewed in Sections 2.1 and 2.2. In Section 3, the performance of the system under jointly partial-time, partial-band jamming is analyzed, and numerical results are provided in Section 4.

2. SYSTEM MODEL AND ANALYSIS

2.1. Transmitter and Receiver

The model we use is an uplink single cell MC-DS-CDMA system with a central controller (CC). A total of Q users share N subcarriers. The physical layer is described in detail in [1]. All Q users occupy the entire frequency band at the same time, and transmit at power P^s on each subcarrier. Different transmitting rates can be achieved by assigning multiple sequences to the same user. We assume that the sequences assigned to the same user are orthogonal to one another, and Pseudo-noise(PN) sequences are used to distinguish the users. QPSK modulation is used on each subcarrier. A square-root-raised-cosine wave shaping filter with roll-off factor $\beta \in [0, 1]$ is used to limit signal bandwidth and avoid inter chip interference.

The wireless channel is assumed to be a frequency-selective

Rayleigh fading channel over the system bandwidth BW. The entire frequency band BW is divided into N subcarriers, each with a bandwidth of BW_0. The subcarrier bandwidth and subcarrier number are chosen to guarantee that each subcarrier undergoes flat fading. The background thermal noise with a double-sided power spectral density of $\eta_0/2$ is added to the received signal.

The receiver structure for user $q's$ i^{th} stream on subcarrier k is given in Fig. 1. A matched filter receiver is used for each of the streams, and the filtered signal is then sampled and despread to produce sequences $y^i_{q,k,I}[n]$ and $y^i_{q,k,Q}[n]$. A reverse operation of the frequency mapping at the transmitter is carried out to produce M partitions of $2R$ terms. Each partition is maximal-ratio combined to produce a diversity-combined test statistic corresponding to each of the M convolutionally coded symbols. These symbols are then deinterleaved and put through a Viterbi decoder.

The jammer is assumed to be a partial-band, partial-time jammer and is on for ρ_T percent of the time, jamming ρ_F percent of the subcarriers when it is on. The jamming waveform being used is narrowband Gaussian noise. The power spectral density of the narrowband interference (NBI) is given by

$$S_J(f) = \begin{cases} \frac{\eta_J}{2}, & \frac{2f_i - BW_0}{2} \leq |f| \leq \frac{2f_i + BW_0}{2}, i = 1, \cdots, N_J \\ 0, & otherwise \end{cases} \tag{1}$$

The partial-time jamming ratio is defined as $0 < \rho_T \leq 1$, and the partial-band jamming ratio is defined as $\rho_F = N_J/N$, where $N_J = 1, 2, ..., N$ is the number of subcarriers being jammed. Let $\eta_{J0}/2$ be the two-sided power spectral density of a full-band, full-time jammer ($\rho_T = 1$, $\rho_F = 1$). For given ρ_T, ρ_F, the two-sided power spectral density for a jammed subcarrier when the jammer is on is given by

$$\frac{\eta_J}{2} = \frac{\eta_{J0}}{2\rho_T\rho_F} \tag{2}$$

2.2. Test Statistics at Receiver

Test statistics at the receiver can be derived by modifying results given in [1] and [2]. The relevant statistics are defined and reviewed in this section. Let $H(k, q)$ be the complex envelope of the channel at subcarrier k between user q and the CC, and let $\alpha(k, q) = |H(k, q)|$.

To calculate the coded error rate, one must first derive the test statistics of $W^{j,i}_{q,l}[n]$ and $W^i_{q,l}[n]$. Since $W^{j,i}_{q,l}[n]$'s are rearranged versions of $y^i_{q,k,*}[n]$'s, they have the same statistics. It was shown in [2] that the expression for $y^i_{q,k,*}[n]$'s has four components: signal component $S^i_{q,k,*}[n]$, multiple-access-interference (MAI) component $I^i_{q,k,*}[n]$, noise component $N^i_{q,k,*}[n]$, and jamming component $J^i_{q,k,*}[n]$. The components have the following properties:

$$S^i_{q,k,*}[n] = \sqrt{P^s}|H(k, q)|s^i_{q,k,*}[n] \tag{3}$$

$I^i_{q,k,*}[n]$ is asymptotically Gaussian in the number of users Q. Its variance can be approximated as

$$Var[I^{(*)}_{q,k,I}[n]] = Var[I^{(*)}_{q,k,Q}[n]] \approx \sum_{r\neq q} P^s \bar{\alpha}^2_r \frac{n_r}{N_c}(1 - \frac{\beta}{4}) \tag{4}$$

as shown in [18]. Here, $\bar{\alpha}_r$ is the average channel gain between user r and the CC.

$N^i_{q,k,*}[n]$ does not depend on the sampling time or the frequency position and is the same for all users. The noise samples are i.i.d complex Gaussian with zero mean and variance $\sigma^2_0 = \eta_0/(2N_c)$.

$J^i_{q,k,*}[n]$ is the same for all users. Let J^I_k and J^Q_k be the jammer component on the in-phase and quadrature channels of subcarrier k, respectively. $J^{I/Q}_k[n]$ is a zero mean, conditionally Gaussian random variable, with variance

$$Var[J^{I/Q}_k[n]] = \frac{1}{N^2_c} \sum_{l=nN_c}^{(n+1)N_c-1} \sigma^2_{J,*}[l] \tag{5}$$

where $\sigma^2_{J,*} = (\alpha^2_J\eta_J)/2$ when the jammer is on, and zero otherwise.

We consider a maximal ratio combiner with operation given by $W^i_{q,l}[n] = \sum_{j=1}^{2R} g^j_q[n]W^{j,i}_{q,l}[n]$, and assume perfect channel state information can be obtained. The coefficient $g^j_q[n]$ has the from

$$g^j_q[n] = \frac{\mathbb{E}\{W^{j,i}_{q,l}[n]|\alpha(\nu(l, j), q)\}}{Var\{W^{j,i}_{q,l}[n]|\alpha(\nu(l, j), q)\}} = \frac{\alpha_{q,\nu(l,j)}}{\sigma^2_{\nu(l,j)}} \tag{6}$$

where $\nu(l, j)$ simply maps the j^{th} copy of the l^{th} symbol to the corresponding subcarrier. Since the jammer is using narrowband Gaussian noise, a MRC using these coefficients will be optimal when soft decision decoding is considered. And finally,

$$W^{j,i}_{q,l}[n] = \begin{cases} y^i_{q,\nu(l,j),I}[\lceil \frac{n}{M} \rceil], & for\ j = 1, \cdots, R \\ y^i_{q,\nu(l,j),Q}[\lceil \frac{n}{M} \rceil], & for\ j = R + 1, \cdots, 2R \end{cases} \tag{7}$$

specifies the mapping between $W^{j,i}_{q,l}$'s and $y_{q,k,*}$'s.

We conclude that $W^i_{q,l}[n]$ is a sum of conditionally independent, jointly Gaussian random variables:

$$W^i_{q,l}[n]|_{\gamma_i} \underset{Q\to\infty}{\to} N(\pm\sqrt{P^s}\gamma_i, \gamma_i) \tag{8}$$

where

$$\gamma_i \triangleq \sum_{j=1}^{2R} \frac{\alpha^2_{q,\nu(i,j)}}{\sigma^2_{\nu(l,j)}} \tag{9}$$

The sign of the mean depends on the transmitted bit, and $\sigma_{\nu(i,j)}$ is the corresponding background noise standard deviation.

3. CODED PERFORMANCE IN FAST FADING

Throughout this section, we use a rate $1/M$ convolutional code with soft-decision Viterbi decoder. We also assume a Rayleigh fading environment. With sufficient interleaving, the vector of M deinterleaved, maximal-ratio combined receiver outputs at time index l is given by $Y_l = [Y_{1,l}, Y_{2,l}, ..., Y_{M,l}]$, where the components of Y_l are independent, conditionally, jointly Gaussian random variables, conditioned on the channel gains between the desired user and the CC. The components of Y_l come from deinterleaving the W^i_q's, and have distributions given by equation (8).

3.1. Individual Symbol Jamming

Without loss of generality, assume we are decoding the 1^{st} stream of user q. Let $b^{(r)}_{i,l}$ be the ith coded symbol of the rth trellis path at time index l for the desired user. Let γ be a vector of SNRs for each of the coded symbols. For a linear binary convolutional code, the coded performance can be evaluated by calculating the conditional probability of selecting a competing path ($r = 1$) over the all-zeros path ($r = 0$).

$$P(U^{(1)} - U^{(0)} \geq 0) = P\left(\sum_{l=1}^{B}\sum_{i=1}^{M} Y_{i,l}\left[b_{i,l}^{(1)} - b_{i,l}^{(0)}\right] \geq 0\right) \tag{10}$$

where B is the truncated depth in the trellis in which all likely error paths remerge with the all-zeros state. Let d_i be the number of code symbol errors. If each of the coded symbols is jammed independently of each other and with probability equal to the partial-time jamming ratio ρ_T, the average probability of selecting $r = 1$ when $r = 0$ was transmitted, given there are d_i symbol differences between $r = 1$ and $r = 0$, can be calculated as

$$\overline{P\left(U^{(1)} - U^{(0)} \geq 0 |\, d_i\right)} = \sum_{j=0}^{d_i}\binom{d_i}{j}\rho_T^j(1-\rho_T)^{d_i-j}P\left(U^{(1)} - U^{(0)} \geq 0\middle|\, d_i, j\right) \tag{11}$$

where $P\left(U^{(1)} - U^{(0)} \geq 0\middle|\, d_i, j\right)$ means selecting $r = 1$ when $r = 0$ was transmitted given there are d_i errors in $r = 1$ and that j of those error symbols were jammed.

We now compute $P\left(U^{(1)} - U^{(0)} \geq 0\middle|\, d_i, j\right)$. Let $\mathcal{E}$ be the set of (i, l) where $Y_{i,l}$ represents an error. Let $\mathcal{J}$ be the set of (i, l) where $Y_{i,l}$ represents a jammed code symbol received in error. By definition, we have their cardinalities satisfy $|\mathcal{E}| = d_i$, $|\mathcal{J}| = j$.

$$\begin{aligned}
&P(U^{(1)} - U^{(0)} \geq 0|d_i, j) \\
&= \mathbb{E}_\alpha\left[P\left(U^{(1)} - U^{(0)} \geq 0\middle|\, d_i, j, \alpha\right)\right] && (12)\\
&< \mathbb{E}_\gamma\left\{\min_{\rho>0}\mathbb{E}_{Y_{i,l}|\gamma}\left[e^{-\rho\left(\sum_{(i,l)\in\mathcal{E}} Y_{i,l}\right)}\middle|\, d_i, j\right]\right\} && (13)\\
&= \prod_{(i,l)\in\mathcal{E}}\mathbb{E}_{\gamma_i^{(l)}}\left\{e^{-\frac{P^s\gamma_i^{(l)}}{2}}\right\} && (14)\\
&= \prod_{(i,l)\in\mathcal{J}}\left(\mathbb{E}\left\{\prod_{k=1}^{2R}\frac{1}{1+\bar{\gamma}_{i,k}^{(l)}}\right\}\right)\prod_{(i,l)\in(\mathcal{E}-\mathcal{J})}\left\{\prod_{k=1}^{2R}\frac{1}{1+\bar{\gamma}_{i,k}^{(l)}}\right\} && (15)\\
&= \prod_{(i,l)\in\mathcal{J}}\left\{\sum_{k=N_{min}}^{N_{max}}\frac{\binom{N_J}{k}\binom{N-N_J}{2R-k}}{\binom{N}{2R}}\left(\frac{1}{1+\bar{\gamma}_J}\right)^k\left(\frac{1}{1+\bar{\gamma}_o}\right)^{2R-k}\right\} \\
&\times \prod_{(i,l)\in(\mathcal{E}-\mathcal{J})}\left\{\prod_{k=1}^{2R}\frac{1}{1+\bar{\gamma}_{i,k}^{(l)}}\right\} && (16)
\end{aligned}$$

where $\gamma = \{\gamma_{i,l}\}_{(i,l)\in\mathcal{E}}$ is a vector of signal-to-noise-ratios. Since the expression of γ solely depends on α when the jammer state is given, averaging over γ is equivalent to averaging over α. In (16), $N_{min} \triangleq \max\{2R - (N - N_J), 0\}$, and $N_{max} \triangleq \min\{N_J, 2R\}$ are, respectively, the minimum and maximum number of diversity components that are being jammed, given there are N_J out of N subcarriers that are jammed. The inequality in (13) comes from the Chernoff bound.

The calculation from (15) to (16) involves averaging over the partial-band jamming status. For a given value of ρ_F, the number of jammed subcarriers ranges from N_{min} to N_{max}, and the probability that k out of $2R$ diversity components are jammed for a given N_J is

$$\frac{\binom{N_J}{k}\binom{N-N_J}{2R-k}}{\binom{N}{2R}}$$

when $N_{min} \leq k \leq N_{max}$ and zero otherwise.

The expressions for $\bar{\gamma}_o$ and $\bar{\gamma}_J$ are given by

$$\bar{\gamma}_o \triangleq \frac{\bar{\alpha}_q^2 P^s}{2(Var[I_q^{\nu(i,k)}[l]] + \sigma_0^2)} = \frac{\bar{\alpha}_q^2 P^s}{2\sigma_B^2} \tag{17}$$

$$\bar{\gamma}_J \triangleq \frac{\bar{\alpha}_q^2 P^s}{2(Var[J_q^{\nu(i,k)}[l]] + \sigma_B^2)} \tag{18}$$

where $\sigma_B^2 = Var[I_q^{\nu(i,k)}[l]] + \sigma_0^2$.

Finally, using the input-output enumeration function of the convolutional code, the union bound on the bit error probability is

$$P_b \leq \sum_{d_i=d_{free}}^{\infty} A(d_i)\overline{P\left(U^{(1)} - U^{(0)} \geq 0 |\, d_i\right)} \tag{19}$$

where d_{free} is the free distance of the code, and $A(d_i)$ is the number of different codewords that are at distance d_i to the $r = 0$ path.

3.2. Burst Jamming ρ_T Fraction of Codeword Symbols

The equation given in (11) is derived for a partial-time jammer that jams each coded bit with equal probability ρ_T. The following proof will show that the result in (11) is also the average bit error probability for a system where a uniform interleaver is used to interleave bits in each codeword, with the jammer picking a random starting point within each codeword and jamming for a duration equal to $\rho_T L$, where L is the length of the entire codeword in coded bits.

To show that (11) applies (in an average sense) to a system with uniform interleaving within a codeword and under a burst jamming attack, we only need to show that the probability of each bit being jammed is equal to ρ_T when averaged over all possible interleavers.

Let $[x_1, x_2, x_3, \cdots, x_L]$ be the codeword bits before the interleaver, and $[z_1, z_2, z_3, \cdots, z_L]$ be the bits after the interleaver. Then, for any fixed index $i \in [1, L]$, the probability that a randomly picked interleaver will map x_1 to z_i is

$$\frac{1!(L-1)!}{L!} = \frac{1}{L} \tag{20}$$

For a jammer that picks a random starting point in each codeword and jams for the duration $\rho_T L$, let $N_{b,J}$ be the nearest integer to $\rho_T L$, so that $N_{b,J}/L \approx \rho_T$. The probability that z_i is jammed is

$$Pr_J(z_i) = \begin{cases} \frac{N_{b,J}}{L-N_{b,J}+1}, & N_{b,J} \leq i \leq L - N_{b,J} + 1 \\ \frac{k}{L-N_{b,J}+1}, & k = i, i < N_{b,J}; \\ & k = L - i + 1, i > L - N_{b,J} + 1 \end{cases} \tag{21}$$

When $N_{b,J} \leq i \leq L - N_{b,J} + 1$, the number of possible starting points for a jammer that could include z_i in the attack is exactly $N_{b,J}$. The two limits for i are found by considering the case when the jammer starts from the first symbol, and when the jammer ends on the last symbol, of the codeword. When $i < N_{b,J}$ and $i > L - N_{b,J} + 1$, the number of starting points for the jammer to include z_i in its attack is less than $N_{b,J}$. For the case $i < N_{b,J}$, the possible starting points to include z_i are from the begining of the codeword to z_i, and there are i locations in total. For the case $i > L - N_{b,J} + 1$,

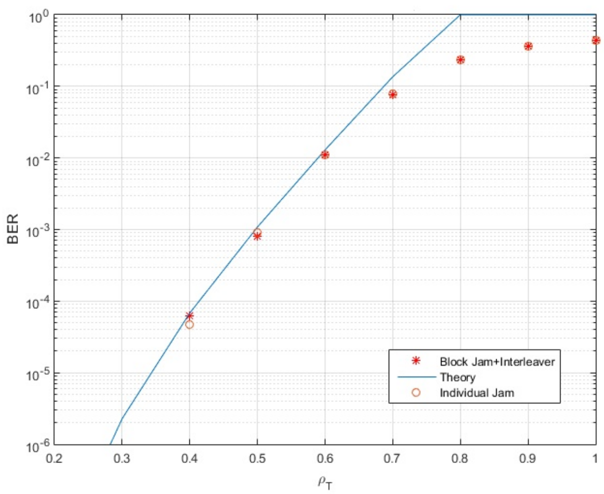

Fig. 2. BER performance with partial time jamming and FEC coding in Rayleigh fading. E_b/N_o=20dB, ISR=10dB, 10 users, M=3, R=3.

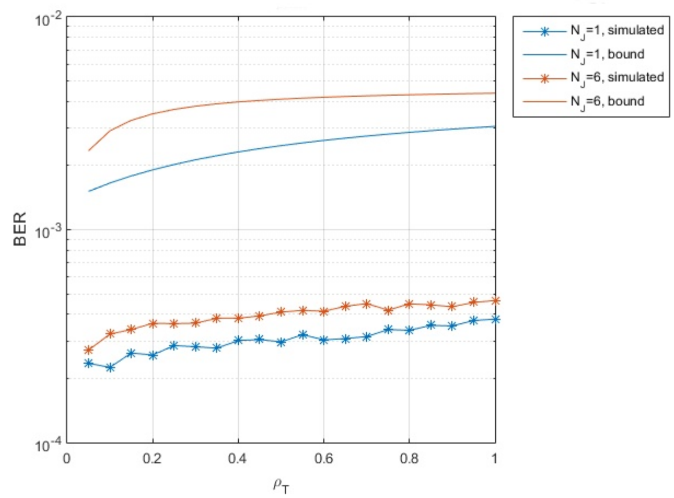

Fig. 3. BER performance with partial-band, partial-time jamming in Rayleigh fading. E_b/N_o=7dB, ISR=15dB, single user, M=3, R=2.

the possible ending points to include z_i are from z_i to the end of the message, and there are $L-i+1$ locations in total.

Dividing the number of possible starting points by the total number of starting points, the result in (21) is obtained. Combining the result (20) and (21), the average probability of x_1 being jammed is

$$P(x_1 \ is \ jammed)$$
$$= \frac{1}{L}\left\{\frac{2}{L-N_{b,J}+1} + \frac{2\times 2}{L-N_{b,J}+1} + \cdots \right.$$
$$\left. +2\frac{N_{b,J}-1}{L-N_{b,J}+1} + [L-2(N_{b,J}-1)]\frac{N_{b,J}}{L-N_{b,J}+1}\right\} \quad (22)$$
$$= \frac{1}{L}\left[\frac{L\cdot N_{b,J}}{L-N_{b,J}+1} - \frac{(N_{b,J}-1)N_{b,J}}{L-N_{b,J}+1}\right] = \frac{N_{b,J}}{L} \approx \rho_T \quad (23)$$

As a result, (11) applies, in an average sense, to the block jamming model when a random interleaver is applied within the codeword. The corresponding bound derived above will also apply to this system, but it will become the bound on the average performance.

4. NUMERICAL RESULTS

In this section, numerical results based on simulation and numerical calculations are presented and discussed. In order to compare the performance of systems with different values of M and R, in the following numerical results, E_b/η_o and ISR (defined below) are controlled.

$$ISR \triangleq \frac{interference \ power}{signal \ power} = \frac{\eta_{J_0}(MRN_{bits})W}{E_b/T_b} \quad (24)$$

In the simulations, the average channel gain between each user and the CC is set to be 1, and the roll-off factor for the wave-shaping filter is chosen to be 0.5. The convolutional code used in this simulation is a rate $1/3$ code with generating polynomial given by [25,33,37] in octal.

4.1. Burst Jammer with Random Interleaver

Fig. 2 compares the simulated average error probability for individual symbol jamming and burst jamming within a codeword with the derived bound given by (11). For this simulation, SNR is fixed to be 20dB per user. The number of users in the system is 10. $N_c = 16$, and a length-1023 pseudo-random sequence is used.

The theoretical result was modified such that whenever the calculated bound for P_b is greater than 1, it is set to 1. Each point is an average of 50,000 bits. The points marked by a star were generated using a randomly selected interleaver and a block jammer. For each realization, a different interleaver is selected and a different starting point was generated for the jammer. A total of 50 interleavers were tested. The points marked by circles were generated when each coded symbol is jammed with equal probability equal to ρ_T.

From the simulation result, it can be seen that when the interleaver structure is not known, the average performance of a block jammer with a randomly selected interleaver is comparable to the average performance of individual symbol jamming. As a result, the result derived based on the individual jamming model can be used as a bound on the average performance. The bound is tight for low BER values and becomes looser as the BER values becomes larger, which is a typical behavior of union-type bounds. To combat the effect of fading and burst jamming, the interleaver in an actual system should have a large enough interleaving depth, such that adjacent branch metrics on the decoding trellis are conditionally independent.

4.2. Joint Partial-band, Partial-time Jammer

Fig. 3 compares simulated partial-band, partial-time jamming with analytic results. The frequency diversity parameter $R=2$ was chosen, E_b/η_o was set to be 7dB, and ISR = 15dB. For each simulated point, a minimum of 5,000 errors were collected. In Fig. 3, simulated and analytic results for partial-band jamming with $N_J = 1$, and full-band jamming with $N_J = 6$ are plotted side-by-side. From this figure, we can see that the analytic result can predict the behavior of the simulated results, and has the potential to be used as a guideline for optimization.

Conclusion: This paper extends the results of [8] by adding noise and error correction, and extends [2] by considering partial-time jamming in addition to partial-band jamming. We intend to continue this research by considering slow fading environments, as well as other types of FEC and jamming.

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