Performance Analysis of FH/MFSK Systems Using Clipper Receiver and Error Correcting Codes Against Band Multitone Jammer in Background Noise Environment

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ABSTRACT In this paper, we derive the symbol error probability for hard decision clipper receivers under the environment with both band multitone jamming and background noise interference. Using the results, we further evaluate pairwise error probabilities for coded systems using majority vote decision decoding without JSI or with JSI. We extensively find the optimum tone jamming strategies from the jammer's view and their worst case pairwise error probabilities from the communicator's view under various levels of background noise interference.

I. INTRODUCTION

Frequency hopping (FH) spread spectrum communication systems [1] can anti-jam hostile interferences and have the capabilities of multiple access and low probability of intercept. In particular, developing various techniques to improve the anti-jamming performance of an FH system under different jamming strategies is a very interesting topic. These techniques use either some kinds of weighting operations or jamming state information to erase the obvious interference [2]-[4]. It has been shown that the most destructive jammer from the communicator's view is the band multitone jammer with n=1 [3], where n is the number of jamming tones appearing on each jammed hop. The performance of the clipper receiver in partial band noise interference environment was investigated in [5]. In this paper, we further analyze the coded performance of the clipper receiver under the environment with both band multitone jamming and background noise interference.

II. SYSTEM MODEL

Consider a frequency hopping M-ary frequency shift keying (FH-MFSK) communication system shown in Fig.1. A binary information sequence generated from the data source is encoded and modulated by a binary input/M-ary output encoder and an MFSK modulator. The system is assumed to be a fast FH system in which the transmitted signal has power level S and carries one M-ary symbol per hop. We also assume the M-ary band is composed of M contiguous frequency slots. One of the M slots is occupied by the transmitted signal, which is called the symbol slot. The other $M-1$ slots are called the side slots. On the other hand, we assume that a hostile band multitone jammer with n=1 distributes its total available power into

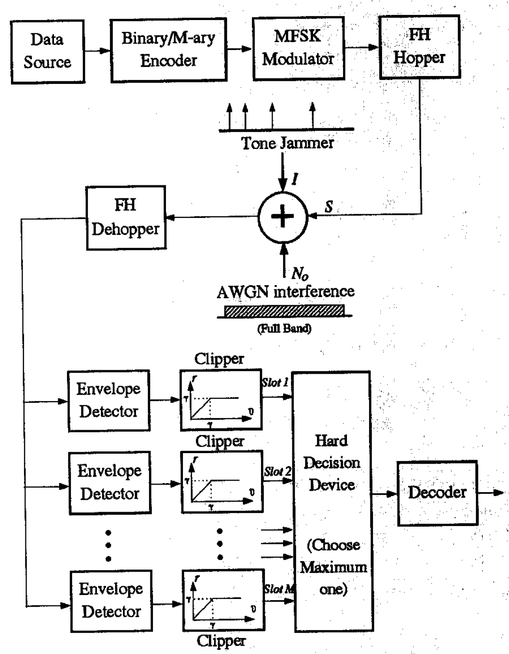

Figure 1: FH-MFSK communication channel model under tone jamming and AWGN interference environment.

a number of random phase CW tones with equal power such that exactly one slot is jammed with power level I if a hop is jammed. In this paper, we only consider this type of jamming strategy and call it "tone jamming". Besides the tone jamming, an AWGN background noise interference with power spectrum density N_o is also added. The received signal is firstly fed into a de-hopper. Then, the de-hopped signal will be fed into M independent noncoherent envelope detectors to detect the received power of M frequency slots within a hop. The output of each envelope detector is followed by a clipper (soft limiters) with an input/output characteristic function of

$$r = \begin{cases} v & \text{when } v < \gamma \\ \gamma & \text{when } v \geq \gamma \end{cases}$$

where γ is the clipping level of each clipper, v is the sample value of the clipper input (i.e., output of the envelope detector) and r is the sample value of the clipper output. Following the clippers, the hard decision device decides the demodulated M-ary symbol by choosing the largest one over M clipper outputs. Output of the hard decision device is then applied to a majority vote decoder.

Without loss of generality, we may assume that each transmitted M-ary symbol has its signal located at the first slot. Hence, the first slot is the symbol slot and other $M-1$ slots are side slots. Moreover, we use r_{1j} and r_{1u} to represent sample values of the symbol slot, and r_{ij} and r_{iu}, $2 \leq i \leq M$, to represent sample values of the ith side slot, where j indicates the slot is jammed and u indicates the slot is unjammed. Therefore, the random variables for the clipper outputs have the following probability density functions :

$$f(r_{1j}) = \begin{cases} \frac{r_{1j}}{N_o} \cdot I_0(\frac{A_c r_{1j}}{N_o}) \cdot e^{\frac{-(r_{1j}^2 + A_c^2)}{2N_o}} & \text{for} \quad r_{1j} < \gamma \\ Q\left(\sqrt{\frac{A_c^2}{N_o}}\,,\, \frac{\gamma}{\sqrt{N_o}}\right) & \text{for} \quad r_{1j} = \gamma \end{cases}$$

$$f(r_{1u}) = \begin{cases} \frac{r_{1u}}{N_o} \cdot I_0(\frac{\sqrt{2S} r_{1u}}{N_o}) \cdot e^{\frac{-(r_{1u}^2 + 2S)}{2N_o}} & \text{for} \quad r_{1u} < \gamma \\ Q\left(\sqrt{\frac{2S}{N_o}}\,,\, \frac{\gamma}{\sqrt{N_o}}\right) & \text{for} \quad r_{1u} = \gamma \end{cases}$$

$$f(r_{ij}) = \begin{cases} \frac{r_{ij}}{N_o} \cdot I_0(\frac{\sqrt{2I} r_{ij}}{N_o}) \cdot e^{\frac{-(r_{ij}^2 + 2I)}{2N_o}} & \text{for} \quad r_{ij} < \gamma \\ Q\left(\sqrt{\frac{2I}{N_o}}\,,\, \frac{\gamma}{\sqrt{N_o}}\right) & \text{for} \quad r_{ij} = \gamma \end{cases}$$

$$f(r_{iu}) = \begin{cases} \frac{r_{iu}}{N_o} \cdot e^{\frac{-r_{iu}^2}{2N_o}} & \text{for} \quad r_{iu} < \gamma \\ e^{\frac{-\gamma^2}{2N_o}} & \text{for} \quad r_{iu} = \gamma \end{cases}$$

where $I_0(\cdot)$ is the zero-order modified Bessel function of the first kind and $A_c^2 = 2S + 2I + 4\sqrt{SI}\cos\phi$ in which S is the signal tone power and ϕ is the tone phase relative to the transmitted signal, uniformly distributed in $[-\pi, \pi]$ and $Q(a\,,\, b)$ is the Marcum Q function defined as

$$Q(a\,,\, b) = \int_b^\infty I_0(at)\, e^{\frac{-(a^2+t^2)}{2}}\, t\, dt$$

In this paper, we do not construct or analyze a system with any specific coding structure. Instead, we only derive the pairwise error probability as the performance measurement of a coded system. Because only linear codes are considered, we may assume that the correct codeword $\mathbf{x}$ is the all-zero codeword. Therefore, the M-ary Hamming distance d of a codeword pair is in fact the number of non-zero symbols of the incorrect codeword $\hat{\mathbf{x}}$. In this paper, we adopt two kinds of decoders. Both of them are based on the majority vote decision (MVD) rules. However, one of them uses the jamming state information (JSI) and the other does not.

In our system model, the equivalent jamming power spectrum density N_J, which is defined as the power level averaged over all the slots of the spread band, equals $\mu \cdot I/M$ where μ is the probability that an M-ary band is jammed by the jamming tone on each hop. Therefore, the ratio of signal energy per encoded symbol, E_s, to equivalent jamming power spectrum density is $E_s/N_J = \frac{M \cdot S \cdot T_h}{\mu \cdot I}$. In addition, the ratio of E_s to N_o is $E_s/N_o = \frac{S \cdot T_h}{N_o}$ where T_h is the dwell interval of one hop.

III. SYMBOL ERROR PROBABILITY OF CLIPPER RECEIVERS

We first derive the uncoded symbol error probability p_s on each hop. For convenience, a random variable z is introduced to indicate the outcome of a received M-ary band where z=0 indicates the whole M-ary band is not jammed, z=1 indicates the symbol slot is jammed and z=2 indicates one of the side slots is jammed. The probabilities for the three outcomes are respectively given by Pr(z=0)=1-μ, Pr(z=1)=μ/M and Pr(z=2)=$\mu(M-1)/M$. Therefore, the symbol error probability p_s will be

$$\begin{aligned} p_s &= \Pr(e \mid z=0) \cdot (1-\mu) + \Pr(e \mid z=1) \cdot \frac{\mu}{M} \\ &+ \Pr(e \mid z=2) \cdot \frac{(M-1) \cdot \mu}{M} \end{aligned} \quad (1)$$

where e is the union of all the independent error events given z. The probabilities for various cases of z can be expressed as

$$\Pr(e \mid z=0) = \Pr(e_1 \mid z=0) + \Pr(e_2 \mid z=0)$$

$$\Pr(e \mid z=1) = \frac{1}{2\pi}\int_{-\pi}^{\pi} [\Pr(e_1|z=1,\phi) + \Pr(e_2|z=1,\phi)]d\phi$$

$$\Pr(e \mid z=2) = \Pr(e_1 \mid z=2) + \Pr(e_2 \mid z=2)$$

where e_1 is an union of the error events occurring when the clipper output of the symbol slot is less than that of one or more side slots and e_2 is an union of the independent error events occurring when the clipper output of symbol slot is equal to γ.

IV. PAIRWISE ERROR PROBABILITY

A. Majority vote decision decoding without JSI

We first consider the decoder using majority vote decision without JSI. Suppose that the channel is M-ary symmetric channel as well as a discrete memoryless channel (MSC-DMC) with symbol error probability p_s. An MVD decoder without JSI operates as follows. For each codeword pair, the decoder chooses the codeword which has the maximal number of code symbols identical to the received word which is obtained using hard decision demodulation. From the derivation of p_s, we see that p_s is a function of multiple parameters including $\gamma_p, S, N_o, I, M, \mu$. where $\gamma_p = \frac{\gamma^2}{2}$ is the clipping level in power. In order to simplify the expression of pairwise error probability, we define a set of system parameters $\mathcal{R} = \{\gamma_p, S, N_o, I, d, M, E_s/N_J,$ "decision rule" $\}$. Note that μ depends on E_s/N_J and $\mu \leq 1.0$. Furthermore, let $\mathcal{R}_1$ be the subset of $\mathcal{R}$, and $\mathcal{R} \ominus \mathcal{R}_1$ be a set which contains all elements in $\mathcal{R}$ excluding those in $\mathcal{R}_1$. For example, $\mathcal{R} \ominus \{\gamma_p, I\} = \{S, N_o, d, M, E_s/N_J,$ "decision rule" $\}$. Therefore, based on the rules of MVD decoding, the pairwise error probability can be shown to be

$$P(\mathbf{x} \to \hat{\mathbf{x}}|\mathcal{R}_{\overline{\text{JSI}}}) = \sum_{i=0}^{\lfloor \frac{d-1}{2} \rfloor} \sum_{j=i+1}^{d-i} \text{Tri}(d,i,j,1-p_s,\frac{p_s}{M-1}) + \frac{1}{2} \cdot \sum_{i=0}^{\lfloor \frac{d}{2} \rfloor} \text{Tri}(d,i,i,1-p_s,\frac{p_s}{M-1}) \quad (2)$$

where $\mathcal{R}_{\overline{\text{JSI}}} = \{\gamma_p, S, N_o, I, d, M, E_s/N_J,$ "MVD without JSI" $\}$ and

$$\text{Tri}\,(n_t,n_1,n_2,p_x,p_y) \triangleq \frac{n_t!}{n_1!\,n_2!\,(n_t-n_1-n_2)!} p_x^{n_1}\, p_y^{n_2}\,(1-p_x-p_y)^{n_t-n_1-n_2}$$

B. Majority vote decision decoding with JSI

If an FH receiver can detect the presence of jamming tones on each hop, then it will be referred as a receiver with JSI. For simplicity, we assume that the detection of jamming state is perfect no matter what level of noise interference is. The case for z=1 is assumed to be an unjamming state because jamming tone in this case is undetectable for the JSI detector. With these assumptions, the channel for hard decision decoding with perfect JSI becomes a two-state (jamming state and unjamming state) MSC-DMC channel with symbol error probabilities p_{sj} for jamming state and p_{su} for unjamming state, respectively. We can easily see that

$$\begin{aligned} p_{sj} &= \Pr(e|z=2) \\ p_{su} &= \frac{\mu \Pr(e \mid z=1) + M(1-\mu)\Pr(e \mid z=0)}{\mu + M(1-\mu)} \end{aligned} \quad (3)$$

where $\Pr(e \mid z=0)$, $\Pr(e \mid z=1)$ and $\Pr(e \mid z=2)$ have been given in (2).

The algorithm for MVD decoding with JSI is described as follows. Suppose the M-ary Hamming distance of two codewords the codeword pair to be decoded is d. We only have to consider the d positions where the two codewords are distinct. Because the JSI is available, the decoder then partitions hard decision output symbols at these d positions into two parts; one contains symbols which are received in jamming state, the other contains symbols which are received in unjamming state. We may call symbols in jamming state erasure symbols and symbols in unjamming state clear symbols. If the number of clear symbols is more than one, MVD is made using clear symbols. Otherwise, MVD is made using erasure symbols. With this decoding algorithm, the pairwise error probability is given by

$$P(\mathbf{x} \to \hat{\mathbf{x}}|\mathcal{R}_{\text{JSI}}) = (1-p_u)^d \cdot P(\mathbf{x} \to \hat{\mathbf{x}}|d\text{erasuresymbols}, \mathcal{R}_{\text{JSI}}) + \sum_{s=1}^{d} \text{Bi}(d,s,p_u) P(\mathbf{x} \to \hat{\mathbf{x}}|s\text{clearsymbols}, \mathcal{R}_{\text{JSI}}) \quad (4)$$

where $\mathcal{R}_{\text{JSI}}=\{\gamma_p, S, N_o, I, d, M, E_s/N_J,$ "MVD with JSI" $\}$, $p_u=\frac{\mu}{M}+(1-\mu)$ is the probability that a symbol is received in unjamming state on each hop and

$$\text{Bi}\,(n_t,n_1,p_x) \triangleq \frac{n_t!}{n_1!\,(n_t-n_1)!} p_x^{n_1}\,(1-p_x)^{n_t-n_1}.$$

In (4), $P(\mathbf{x} \to \hat{\mathbf{x}}\ |d$ erasure symbols, $\mathcal{R}_{\text{JSI}})$ is the pairwise error probability of MVD decoding given d erasure symbols are received in jamming state, which can be shown to be

$$\begin{aligned} &P(\mathbf{x} \to \hat{\mathbf{x}} \mid d \text{ erasure symbols}, \mathcal{R}_{\text{JSI}}) \\ &= \sum_{i=0}^{\lfloor \frac{d-1}{2} \rfloor} \sum_{j=i+1}^{d-i} \text{Tri}\,(d,i,j,1-p_{sj},\frac{p_{sj}}{M-1}) \\ &+ \frac{1}{2} \cdot \sum_{i=0}^{\lfloor \frac{d}{2} \rfloor} \text{Tri}\,(d,i,i,1-p_{sj},\frac{p_{sj}}{M-1}) \end{aligned} \quad (5)$$

Finally, $P(\mathbf{x} \to \hat{\mathbf{x}} \mid s$ clear symbols, $\mathcal{R}_{\text{JSI}})$ in (4) is the pairwise error probability under the condition that s out of d hard decision outputs are received in unjamming state, which can be shown to be

$$\begin{aligned} &P(\mathbf{x} \to \hat{\mathbf{x}} \mid s \text{ clear symbols}, \mathcal{R}_{\text{JSI}}) \\ &= \sum_{i=0}^{\lfloor \frac{s-1}{2} \rfloor} \sum_{j=i+1}^{s-i} \text{Tri}\,(s,i,j,1-p_{su},\frac{p_{su}}{M-1}) \\ &+ \frac{1}{2} \cdot \sum_{i=0}^{\lfloor \frac{s}{2} \rfloor} \text{Tri}\,(s,i,i,1-p_{su},\frac{p_{su}}{M-1}) \end{aligned} \quad (6)$$

V. DISCUSSIONS

Based on the equations we derived in previous sections, the pairwise error probabilities for both kinds of decoding algorithms with clipper receivers can be numerically calculated. For simplicity, we set S to be 1.0 and normalize the parameters N_o, I and γ_p to relative values of $S=1$ through the rest of paper. In addition, the dwell interval of a hop T_h is also assumed to be unity in all our discussions. The following subsections are prepared for different jamming situations. Interpretations for the numerical data are provided.

A. Optimum Tone Jamming versus E_s/N_o

Consider a jamming versus anti-jamming situation in which the clipping level is fixed. We assume that the clipping level is fixed and the tone jammer has information about the level of noise interference at the receiver end. Therefore, it is possible for the power constrained jammer to choose the optimum power level of jamming tone, I_{opt}, to maximize the pairwise error probability. That is

$$I_{opt} = \max_{I_{min} \le I \le I_{max}} P(\mathbf{x} \to \hat{\mathbf{x}}|I, \mathcal{R}_2) \quad (7)$$

where $I_{min} = \frac{M\,S}{(E_s/N_J)}$, which appears at $\mu=1.0$, I_{max} is the total available power of jammer and $\mathcal{R}_2 = \mathcal{R} \ominus I$ is a set of system parameters excluding I. Note that the error probability caused by optimal jamming tone power I_{opt} is referred to be the worst case pairwise error probability, P_{wc}, which can be expressed as $P_{wc}=P(\mathbf{x} \to \hat{\mathbf{x}}|I_{opt}, \mathcal{R}_2)$.

(A) From the jammer's view, we now examine the optimum jamming strategy when the MVD rule without JSI is used. Fig.2(a) shows I_{opt} versus E_s/N_o for various combinations of E_s/N_J, d and γ_p given $M=4$. From curve (II) of Fig.2(a)

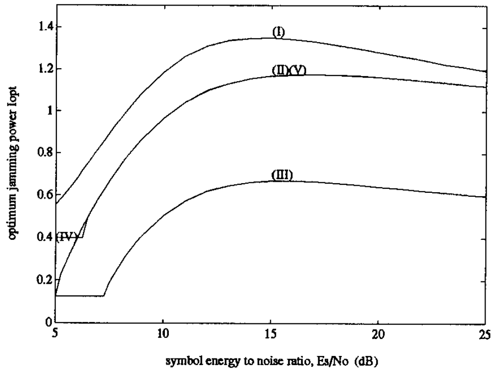

Figure 2(a): I_{opt} versus E_s/N_o for various combinations of E_s/N_J, d and γ_p when M=4 and MVD rule without JSI are considered.

curve (I) : $E_s/N_J = 15$dB, $d = 3$, $\gamma_p = 10.0$
curve (II) : $E_s/N_J = 15$dB, $d = 3$, $\gamma_p = 1.0$
curve (III) : $E_s/N_J = 15$dB, $d = 3$, $\gamma_p = 0.5$
curve (IV) : $E_s/N_J = 10$dB, $d = 3$, $\gamma_p = 1.0$
curve (V) : $E_s/N_J = 15$dB, $d = 5$, $\gamma_p = 1.0$

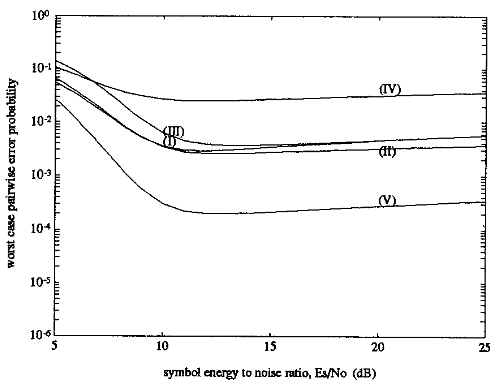

Figure 2(b): P_{wc} versus E_s/N_o under the value of I_{opt} in Fig.2(a).

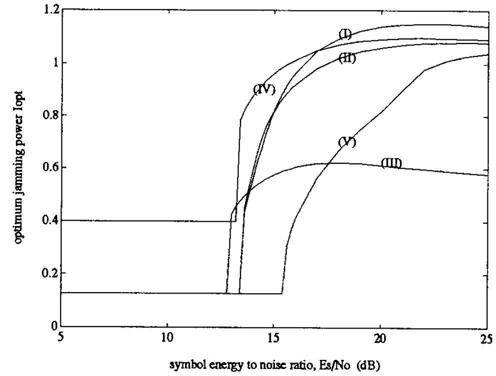

Figure 3(a): I_{opt} versus E_s/N_o for various combinations of E_s/N_J, d and γ_p when M=4 and MVD rule with JSI are considered.

curve (I) : $E_s/N_J = 15$dB, $d = 3$, $\gamma_p = 10.0$
curve (II) : $E_s/N_J = 15$dB, $d = 3$, $\gamma_p = 1.0$
curve (III) : $E_s/N_J = 15$dB, $d = 3$, $\gamma_p = 0.5$
curve (IV) : $E_s/N_J = 10$dB, $d = 3$, $\gamma_p = 1.0$
curve (V) : $E_s/N_J = 15$dB, $d = 5$, $\gamma_p = 1.0$

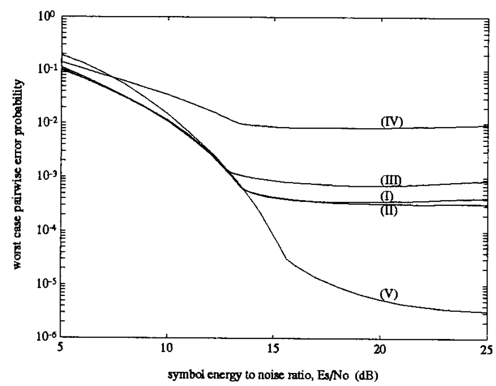

Figure 3(b): P_{wc} versus E_s/N_o under the value of I_{opt} in Fig.3(a).

which is specified by E_s/N_J=15dB, d=3 and γ_p=1.0, we see that the value of I_{opt} slowly increases from the point 1.122 as E_s/N_o decreases. The phenomenon indicates when noise interference increases the jammer must concentrate more jamming power on each tone to increase the jamming efficiency. However, after a peak, curve (II) goes down and then terminates at the point 0.126 (=I_{min}) for E_s/N_o =5dB. That means, when the channel is noisy, error events due to noise interference frequently occur. In this situation, a better choice of jamming strategy is spreading the total available jamming power into more jamming tones to enhance the jamming effect. From curves (II), (IV) and (V) which have the same value of γ_p but distinct in E_s/N_J and d, we find I_{opt} is almost independent of E_s/N_J and d. In other words, during the optimization of I_{opt}, E_s/N_J and d need not be taken into account.

(B) From the communicator's view, we now investigate the worst case pairwise error probabilities, P_{wc}, for MVD rules without JSI. Fig.2(b) shows P_{wc} versus E_s/N_o where P_{wc} is related to the corresponding value of I_{opt} in Fig.2(a). In Fig.2(b), we find that when E_s/N_o>10dB curve (II) for γ_p=1.0 gives better performance than both curve (I) for γ_p=10.0 and curve (III) for γ_p=0.5. That implies it is not the best choice for a clipper receiver with either slight-clipping (γ_p=10.0) or over-clipping (γ_p=0.5) when a jammer can apply the optimum jamming strategy. However, when E_s/N_o <10dB, the performance of curve (I) is better than that of curve (II). As a rule of thumb, when the background noise is negligible, γ_p can be chosen in the vicinity of 1.0 and when the channel is noisy, γ_p must be increased.

(C) In this part, we examine the optimum jamming strategy from the jammer's view when the MVD with JSI is used. The curves in Fig.3(a) have the same system parameters as the corresponding curves in Fig.2(a) except that MVD rule with JSI is used. We now use curve (II) in Fig.3(a) to explain the variation of I_{opt} versus E_s/N_o as follows. When E_s/N_o is high, noise interference is negligible and the probability that errors occur at part of clear symbols is also negligible. In such a case, most of the errors may occur when the decision is made by using erasure symbols only. Therefore, from the jammer's view, the value of I_{opt} must be assigned to be larger than $\min\{\gamma_p, S\}$ to efficiently produce errors to the symbols received in jamming state. When the level of noise interference becomes significant, two kinds of error events implicit in (4) are possible. One results from tone jamming, the other results from noise interference. For the latter, the probability of errors depends on the the number of clear symbols which are used to make decision by the decoder. In other words, the less clear symbols the decoder can use, the higher probability of decoding errors the decision will be. Hence, the strategy of tone jamming in this situation is to produce erasure symbols so that the receiver removes them and makes decision using only a small amount of clear symbols. Therefore, in order to maximize the pairwise error probability, the choice of I_{opt} involves the consideration of producing both kinds of errors. When the channel is very noisy, it is difficult for the tone jammer to produce the first kind of errors due to noise interference. Instead, the strategy of an intelligent jammer is spreading more jamming tone into the spread band by reducing jamming power on each tone and producing more erasure symbols to introduce more errors of the second kind. Therefore, when the level of noise interference rises above a critical value, full band jamming (μ=1) with $I_{opt}=I_{min}$ becomes the optimum strategy from the jammer's view.

From curves (II), (IV) and (V) in Fig.3(a), which have identical γ_p but different E_s/N_J and d, we find I_{opt} is also a function of E_s/N_J and d. Therefore, the parameters γ_p, E_s/N_J, d and total available jamming power must be taken into account in the optimum jamming strategy.

(D) In this part, we make a comparison between the MVD rule with JSI and that without JSI from the performance of the worst case pairwise error probabilities. Fig.3(b) shows the worst case pairwise error probabilities for MVD rules with JSI. From curve (II) in Fig.2(b) and that in Fig.3(b), we find MVD rule with JSI is obviously superior to that without JSI when E_s/N_o >12dB. But, the fact is reversed for E_s/N_o <12dB. This phenomenon shows that performance improvement using the MVD rule with JSI is valid only when the background interference is low.

B. Optimum Tone Jamming versus Clipping Level

We now consider the optimum tone jamming strategy versus the clipping level given E_s/N_o. Fig.4(a) shows I_{opt} versus γ_p for various values of E_s/N_o when M=4, E_s/N_J= 15dB and MVD rule without JSI are given. From Fig.4(a), we find I_{opt}, on each curve, is roughly proportional to γ_p when γ_p< 1.0. Furthermore, I_{opt} is always greater than γ_p except the curve for E_s/N_o=8dB. The offset between I_{opt} and γ_p is required by the optimum jammer to increase the reliability of jamming effect. On the other hand, when $\gamma_p \geq 1.0$, I_{opt} asymptotically approaches toward a constant value as γ_p increases. This phenomenon indicates the clipping level must be chosen in the vicinity of signaling tone power to obtain a satisfactory clipping effect. Fig.4(b) shows P_{wc} versus E_s/N_o, where P_{wc} is related to the corresponding value of I_{opt} in Fig.4(a). It is seen that

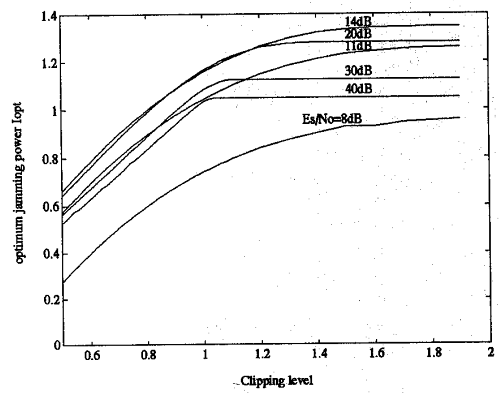

Figure 4(a): I_{opt} versus γ_p for various E_s/N_o when MVD rule without JSI is employed (M=4, E_s/N_J=15dB, d=3).

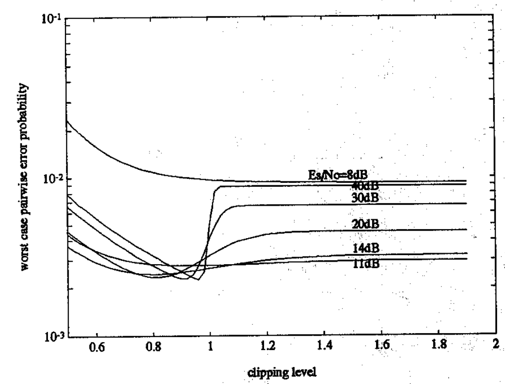

Figure 4(b): P_{wc} versus γ_p under the value of I_{opt} in Fig.4(a).

there exists an optimum γ_p for the clipper receiver to minimize the worst case pairwise error probability. The value of optimal γ_p is always nearby but less than 1.0 when E_s/N_o>14dB.

With the same system parameters as specified in Fig.4(a), we investigate the behavior of I_{opt} versus γ_p, from Fig.5(a), for various E_s/N_o when MVD rule with JSI is used. It is seen that the variation of I_{opt} versus γ_p is similar to that in Fig.4(a) for the curves with $E_s/N_o \geq$20dB. Moreover, when the channel becomes noisy, I_{opt} will be independent of γ_p for the curves with $E_s/N_o \leq$11dB. On the other hand, Fig.5(b) shows P_{wc} versus E_s/N_o where P_{wc} correspond to the values of I_{opt} in Fig.5(a). We find the curve with E_s/N_o=20dB has the best performance over the curves for γ_p>1.0 in Fig.5(b). The phenomenon indicates that a suitable level of noise interference provides some positive contribution in lowering the error probabilities from the communicator's view when clipping is loose.

VI. CONCLUSIONS

In this pape, we find that the performance for MVD decoding with JSI is better than that for MVD decoding without JSI when noise interference is low. This condition is reversed when noise interference is high. We also find that the optimum value of the

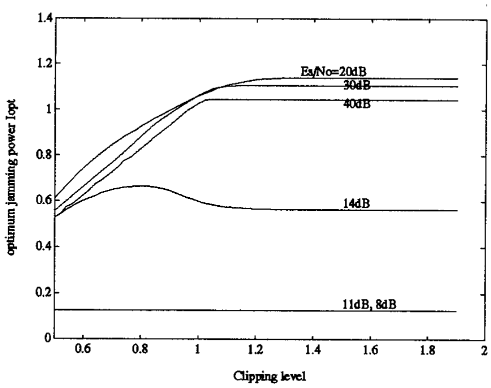

Figure 5(a): I_{opt} versus γ_p for various E_s/N_o when MVD rule with JSI is employed (M=4, E_s/N_J=15dB, d=3).

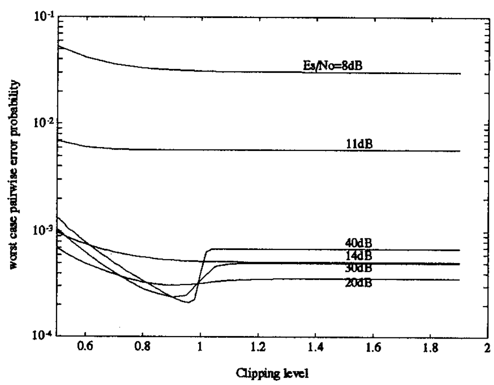

Figure 5(b): P_{wc} versus γ_p under the value of I_{opt} in Fig.5(a).

clipping level is always less than the signaling power level in low to moderate interference conditions.

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