Performance of Follower Noise Jammers Considering Practical Tracking Parameters

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***Abstract*—In this paper, we analyze the performance of Follower Noise Jammers (FNJ) considering three practical tracking parameters such as tracking bandwidth, tracking time and tracking success probability. The performance of FNJ is compared with that of the Partial-Band Noise Jammer (PBNJ) in terms of Symbol Error Rate (SER) under the assumed typical operation scenario. As we can easily expect, it is observed that the performance of FNJ is better than that of PBNJ in the sense of jamming. It is also observed that the performance of FNJ is heavily dependent on the tracking time and the tracking success probability and, at the same time, the effect of the tracking bandwidth on the performance of FNJ is relatively small compared with the other two parameters. Finally, we show the required tracking time and tracking success probability to satisfy a certain required SER for a fixed tracking bandwidth under the assumed operation scenario.**

I. INTRODUCTION

Performance of a certain military tactical communication system is usually evaluated by the Low Probability of Intercept (LPI) and the Anti-Jamming (AJ) characteristics [1-3]. Signal interception is typically composed of following four processes: (i) Cover : find where the interesting signal is located in the frequency band, (ii) Detect : determine whether the signal is transmitted or not, (iii) Intercept : extract the instantaneous frequency, signal waveform, timing information of the signal, and, finally, (iv) Exploit : restore the original information of the transmitted signal such as voice, image, text and so on using the intercepted and extracted information of the signal [1]. For an Electronic warfare Support (ES), the above-mentioned four steps are equally important. However, for an Electronic Attack, after the cover and the detect processes, a jamming signal is immediately radiated to interfere the communication signals.

As a practical way to improve LPI and AJ characteristics of tactical communications, Spread Spectrum (SS) communications are widely used in the world [1-5]. Direct Sequence (DS)-SS and Frequency Hopping (FH)-SS communications are currently used as a way of spreading the information signal. In DS-SS communications, the information signal is directly multiplied by the spreading code, i.e., spreading chip sequence. In FH-SS communications, the carrier frequency is changed on a hop-by-hop basis according to the hopping sequence. At the communicator's point of view, in order to improve the LPI and AJ characteristics of SS communications by widening the spreading bandwidth, FH-SS communications are easier to use wider bandwidth than DS-SS communications, because the chip rate of DS-SS communications is difficult to be shortened enough to provide wide spreading bandwidth. Hence, FH-SS communications are more desirable than DS-SS communications in the sense to further improve the LPI and the AJ characteristics. In this paper, we consider the FH-SS signal as our target signal.

In order to intentionally interfere the military tactical communication signals, various jamming techniques are proposed and analyzed [2,3]. Jamming techniques can be categorized into noise jamming, tone jamming and so on, based on the characteristics of the jamming signal source. Noise jamming is sub-categorized into the wideband noise jamming and partial-band noise jamming based on the jamming noise bandwidth. In addition, tone jamming is also sub-categorized into single-tone jamming and multi-tone jamming based on the number of jamming tones. Against the FH-SS communications, partial-band noise jamming and tone jamming are commonly used in order to improve the jamming performance as the spreading bandwidth increases [6].

Generally speaking, however, the jamming performance of the fore-mentioned partial-band noise jamming and tone jamming is also degraded as the spreading bandwidth increases. As the spreading bandwidth increases and, resultantly, the jamming performance is degraded, follower jamming techniques are extensively studied in order to overcome the drawbacks of partial-band jamming and tone jamming [7-9]. However, in the past literatures, the lack of considerations for the practical tracking parameters of the follower jammers results in the insufficient analysis for the performance of follower jammers. In this paper, we consider three basic tracking parameters of the follower jammers such as tracking bandwidth, tracking time and tracking success probability in order to practically analyze the performance of follower jammers. In addition, we compare the performance of follower jammers with that of the optimum partial-band jammers to show the superiority of the follower jammers over the partial-band jammers.

This paper is organized as follows: In Section II, we briefly review the concept of the partial-band jamming and follower jamming, and address the tracking parameters of follower

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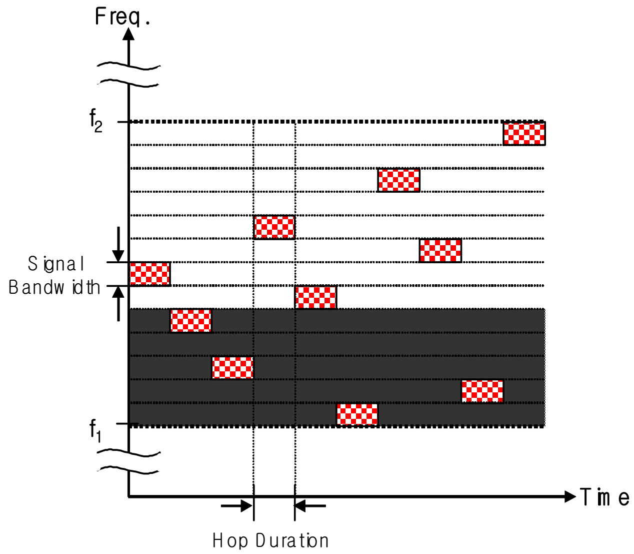

Figure 1. Conceptual Diagram of Partial-Band Noise Jamming

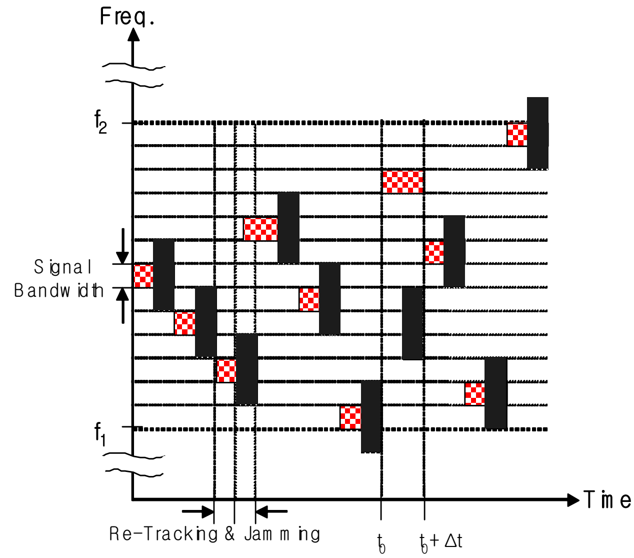

Figure 2. Conceptual Diagram of Follower Noise Jamming

jammers. In Section III, we show the assumed system model including transmitter, receiver and jammer characteristics. Then, we discuss the analysis results. Finally, the concluding remarks and the further works are given in Section IV.

II. Follower Jammers: Concepts & Tracking Parameters

A. *Partial-Band Noise Jamming (PBNJ)*

Figure 1 and Figure 2 show the conceptual diagrams of the partial-band noise jamming and the follower noise jamming, respectively, on a time-frequency domain, where x-axis and y-axis represent the time domain and the frequency domain, respectively. In these figures, the overall hopping bandwidth is assumed (f_2-f_1). Before we discuss the concepts of the follower jammer, in this sub-section we briefly review the concepts of partial-band jamming. In this paper, we focus on the noise jamming as a jamming signal source of jammers.

In case of the wideband noise jamming, the jammer's noise bandwidth is typically same as the overall hopping bandwidth. In this case, as the overall hopping bandwidth, i.e., spreading bandwidth increases linearly, the jammer's noise power spectral density decreases linearly. When the hopping bandwidth becomes large, the jammer's noise power spectral density becomes very low and, subsequently, the jamming performance rapidly degrades. In order to overcome this shortcoming of the wideband noise jamming, the partial-band noise jamming was proposed.

In case of the partial-band noise jamming, the jammer's noise bandwidth is smaller than that of the wideband noise jammer, so that only some parts of the overall FH signals are jammed. Consequently, the Partial-Band Noise Jammer (PBNJ) can jam only some parts of FH signals with a higher noise power spectral density than the Wide-Band Noise Jammer (WBNJ). Resultantly, if the FH signal hops into the jamming bandwidth, the PBNJ can effectively jam the FH signal. Generally, for a wider FH bandwidth, PBNJ is more effective and results in higher Symbol Error Rate (SER) than WBNJ.

Compared with the Follower Noise Jammer (FNJ) explained in the next sub-section, it is noticeable that the performance of PBNJ can be easily evaluated by the frequency domain analysis of the jamming probability [2,3]. In order to obtain the optimum partial-band noise jamming, the key factor is to determine the noise bandwidth of PBNJ under a certain limited jamming power.

B. *Follower Noise Jamming (FNJ) and Tracking Parameters*

Figure 2 shows the conceptual diagram of follower noise jamming. As shown in Figure 2, in order to jam the FH signal, it is essential to re-track the hopped signal frequency within the hop duration for each hop. In other words, in case of FNJ, it is required for the follower jammer to find the hopped frequency at first, and then the jammer's noise signal is transmitted during the remaining time of the hop.

As we can intuitively foresee through the figure, the performance of the FNJ is determined mainly by the following three tracking parameters: (i) Tracking bandwidth, which is equivalent to the frequency resolution of FNJ and means how accurately the FNJ can re-track the FH signal, and it is related with the hardware complexity of FNJ's receiver, (ii) Tracking time, which is defined as the required time to re-track the FH signal in each hop, and this also indicates the remaining time in which the FNJ can jam the FH signal, and, finally, (iii) Tracking success probability, which corresponds to the probability that the FNJ can successfully re-track the hopped frequency within a certain limited tracking time.

Figure 2 shows an example that 50% of the hop duration is used to re-track the hopped frequency and the remaining 50% of the hop duration is used for jamming. During the time duration (t_0, $t_0+\Delta t$), the figure shows an example of tracking failure, so that the jammer jams a wrong frequency band. In this paper, we investigate the performance of FNJ in terms of above-addressed three tracking parameters such as tracking bandwidth, tracking time and tracking success probability.

C. Performance Analysis of FNJ

For a given jammer's noise power, P_j, the received noise power at the communication receiver, $P_{rec,j}$, can be represented by

$$P_{rec,j} = P_{j,eff} G_{jr} G_{rj} h_j^2 h_r^2 d_{jr}^{-4} \quad (1)$$

where $P_{j,eff}$ is effective jamming power considering the noise bandwidth of jammers, G_{jr} and G_{rj} are the antenna gain of jammer to receiver and receiver to jammer, respectively, h_j and h_r are the antenna height of jammer and receiver, respectively, and d_{jr} is the distance from jammer to receiver. For the channel model, '2-Ray Earth Reflection Model' is used [3]. By the same way, the received signal power, $P_{rec,s}$, can be represented by

$$P_{rec,s} = P_s G_{tr} G_{rt} h_t^2 h_r^2 d_{tr}^{-4} \quad (2)$$

where P_S is the signal transmission power, G_{tr} and Grt are the antenna gain of transmitter to receiver and receiver to transmitter, respectively. h_t is the antenna height of transmitter, and d_{tr} is the distance from transmitter to receiver.

Jammed and unjammed Signal-to-Noise power Ratio (SNR) in a hop duration can be respectively represented

$$SNR_{jam} = P_{rec,s} / \left(P_{rec,j} + N_0\right) \quad (3)$$

and

$$SNR_{unjam} = P_{rec,s} / N_0 \quad (4)$$

where N_0 is the noise power spectral density. Then, the symbol error rate of FNJ can be written

$$\begin{aligned} SER_{FNJ} &= \Pr\{SNR_{jam}\} \cdot (1 - T_{track}) \cdot (P_{success}) \\ &+ \Pr\{SNR_{unjam}\} \cdot [1 - (1 - T_{track})(P_{success})] \end{aligned} \quad (5)$$

where $\Pr\{\cdot\}$ is the SER equation of BFSK signaling [4]. T_{track} and $P_{success}$ are the tracking time and the tracking success probability of FNJ, respectively.

III. System Model and Analysis Results

A. System Model

We assume the following parameters for the transmitter and the FH signal: FH signal spreading bandwidth is 100MHz and the hop rate is 100hops/sec. Binary Frequency Shift Keying (BFSK) is used between the transmitter and the receiver. The BFSK symbol rate is 10ksymbols/sec and BFSK signal bandwidth is 20kHz. Signal transmission power is 5W, and transmitter antenna gain and height are 3dB and 3m, respectively.

We assume the following parameters for the receiver and the distance between transmitter, jammer and receiver: Receiver antenna gain to the direction of transmitter and jammer are 3dB and -3dB, respectively, considering the side-lobe jamming situation of PBNJ and FNJ. Receiver antenna height is 3m. In addition, the distances from transmitter to receiver and from jammer to receiver are assumed 5km and 20km, respectively, considering that it is more likely for the jammer to be located further away from the receiver than the transmitter.

We assume the following parameters for the jammer: Total jamming power is 100W. Jammer antenna gain and height are 3dB and 6m, respectively.

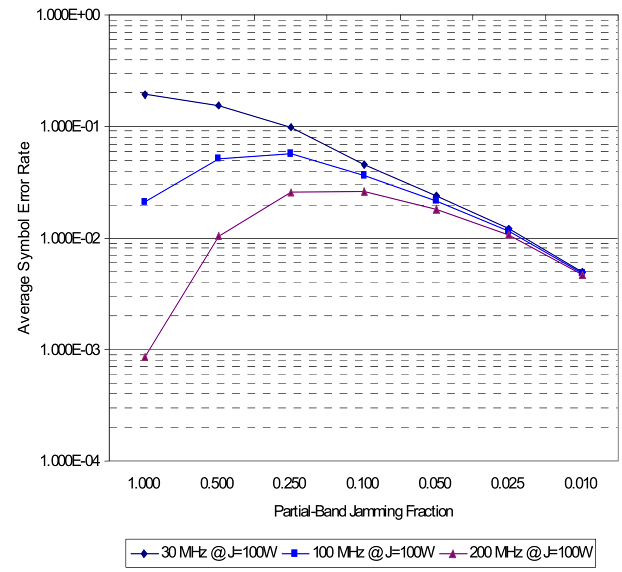

Figure 3. Average SER of Partial-Band Noise Jamming (PBNJ).

B. Analysis Results

Figure 3 shows the average SER performance of PBNJ. For the comparisons, the FH signal spreading bandwidth of 30, 100, 200MHz are considered. In the figure, the partial-band jamming fraction is defined as the ratio of the partial-band jamming bandwidth over the FH signal spreading bandwidth. In addition, when the partial-band jamming fraction equals to 1, the performance of PBNJ corresponds to that of WBNJ.

When the FH signal spreading bandwidth is small enough, WBNJ is more effective than PBNJ, as we can see in the figure. However, as the FH signal spreading bandwidth increases, PBNJ becomes more effective than WBNJ. In addition, as proved in the previous literatures [2,3], when the FH signal spreading bandwidth increases, the optimum partial-band jamming fraction also decreases. The obtained worst-case SER for the FH signal spreading bandwidth of 100MHz, named worst-case PBNJ, is used for the performance comparison between the optimum PBNJ and the FNJ in the following figures.

In Figure 4 and Figure 5, the optimum follower jammer corresponds to the case that (i) the tracking bandwidth is equal to the BFSK signal bandwidth, (ii) the tracking time is 0, and

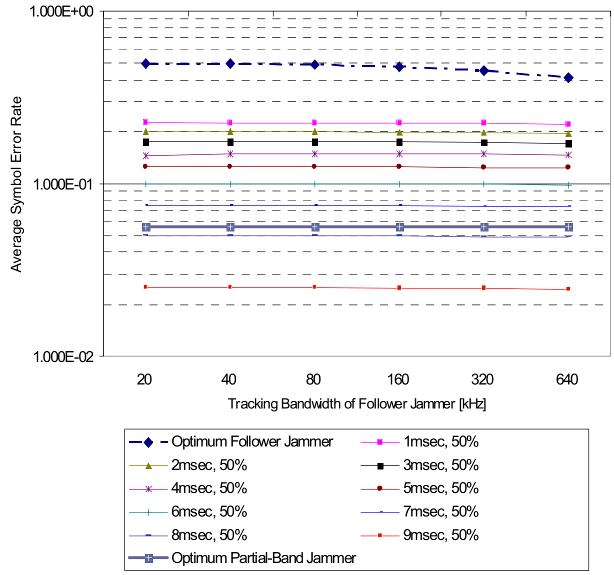

Figure 4. Average SER of Follower Noise Jammer (FNJ) considering the tracking time variations.

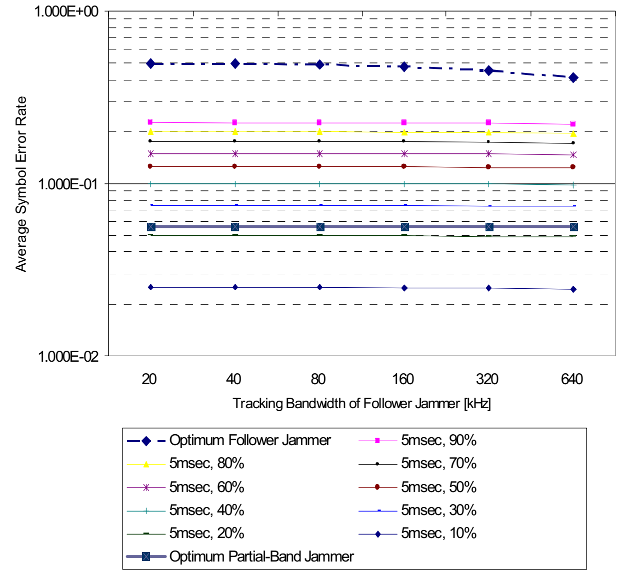

Figure 5. Average SER of Follower Noise Jammer (FNJ) considering the tracking success probability variations.

(iii) the tracking success probability is equal to 1. In addition, the optimum partial-band jammer corresponds to the worst-case SER of PBNJ.

Figure 4 shows the average SER performance of FNJ according to the various values of tracking bandwidths considering the tracking time variations, where the tracking success probability is assumed to be 50%. In the figure, we can observe that the jamming performance is degraded as the tracking time increases. In other words, as the tracking time increases, the average SER decreases. However, as long as the tracking time is less than 7msec, the jamming performance of the FNJ is better than that of the optimum PBNJ. In other words, under the assumed system model with the tracking success probability of 50%, the FNJ shows the better jamming performance than the optimum PBNJ, if the re-tracking is completed within 7msec among the hop duration of 10msec.

Figure 5 shows the average SER performance of FNJ according to the various values of tracking bandwidths considering the tracking success probability variations, where the tracking time is assumed to be 5msec, which is the half of the hop duration. In the figure, the jamming performance is enhanced as the tracking success probability increases. For the tracking success probability of more than 30%, the FNJ shows better jamming performance than the optimum PBNJ. In other words, under the assumed system model with the tracking time of 5msec, the FNJ shows the better jamming performance than the optimum PBNJ, if the tracking success probability is greater than 30%. In Figure 5, we can see that, in order to enforce more than 10% of average SER to the communication receiver, the tracking success probability should be bigger than 40% for the tracking bandwidth up to 160kHz and, at the same time, the tracking should be completed within 5msec, which is equal to

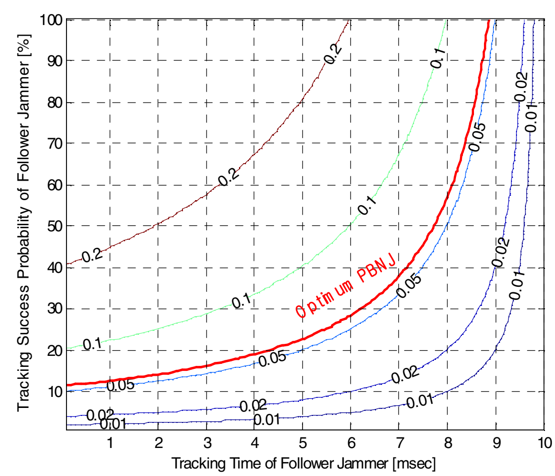

Figure 6. Various combinations of the tracking time and tracking success probability satisfying a certain average Symbol Error Rate (SER).

the half of the hop duration.

Figure 6 shows more precise plot of the various combinations of tracking time and tracking success probability of FNJ which satisfy a certain required average SER as a FNJ's point of view, where the expected average SER is marked over each curve. The tracking bandwidth is assumed to be 160kHz which is 8 times bigger than the BFSK signal bandwidth. In addition, for the comparisons, the SER performance of the optimum PBNJ is plotted together. The figure can be used as a reference figure to find a desired combination of tracking time and tracking success probability of FNJ, when we design a FNJ system. For example, when the required average SER is equal to 10%, we can trade-off among several combinations of tracking time and tracking success probability such as (2msec, 25%), (5msec, 40%) or (7msec, 70%) and, finally, we can choose one of the combinations depending on the hardware and software constraints of the designed system.

IV. Concluding Remarks and Further Works

In this paper, we compared the average SER performance of the Partial-Band Noise Jammer (PBNJ) and Follower Noise Jamming (FNJ). We considered three practical parameters for the FNJ such as the tracking bandwidth, tracking time and tracking success probability in order to practically analyze the average SER performance of the FNJ, and compare it with that of the optimum PBNJ. Through the analysis results, under the assumed system model, the effect of the tracking bandwidth on the performance of the FNJ is relatively small compared with that of the tracking time and the tracking success probability. In addition, as an Electronic Attack (EA)'s point of view, the FNJ shows better jamming performance than the PBNJ. In order to enforce a certain desired average SER to the communication receiver, various combinations of the tracking time and the tracking success probability are possible, and one of them can be chosen based on the hardware and software performances and requirements of the FNJ.

As a further work, it is needed to further consider the more detailed model for the re-tracking mechanisms and its hardware such as filter-band combiners, FFT receivers and other wideband scanning receivers. In addition, in this paper, we only considered noise jamming for the follower jammer, it is desired to extend its scope to the tone jamming for the follower jammer considering the similar approach for the practical tracking parameters.

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