FOLLOWER JAMMER CONSIDERATIONS FOR FREQUENCY HOPPED SPREAD SPECTRUM

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ABSTRACT

In this paper design considerations to be used to account for follower jamming of frequency hopping (FH) spread spectrum systems are presented. A follower jammer attempts to determine the hop frequency with a "determinator" circuit, and then generates jamming in a range about that frequency. Geometrical considerations show the spatial limit at which follower jamming becomes impossible. The minimum determination time and the probability of correct determination, P_{hc}, are derived as a function of the intercepted SNR, and the determinator resolution. Both fast hopping (one or more hops per information symbol) and slow hopping are analyzed. The use of follower jammers against hopped FDMA systems is also discussed. A summary design recipe is given. It is concluded that the vulnerability to follower jammers can be reduced to tolerable levels by use of current practical hop rates.

INTRODUCTION

Frequency hopping (FH) spread spectrum is particularly useful to combat jamming primarily because it is relatively easy to operate over very large spread bands. However, FH can be efficiently jammed by follower (also called "repeat-back") jammers under certain conditions. In follower jamming, the jammer intercepts the transmitted signal, tries to determine the frequency of the hop, and then generates jamming in a narrow range about this frequency. It is the purpose of this paper to discuss design considerations to account for such jammers.

In designing an anti-jam FH system, the spread bandwidth, W_{ss}, is usually fixed at the start, and often is just the bandwidth available. Practical systems use fixed hop rates, or, at most, a few selectable hop rates. The data rate is often the only thing that is allowed to vary as jamming levels change. The selection of the particular fixed hop rate, R_h, is based on a number of tradeoffs [1]. The tradeoff related to the follower jammer threat is how high to make the hop rate so as to reduce the vulnerability to follower jamming to an acceptable level.

Geometrical protection against follower jammers is well known, but will be reviewed here. What is not well studied are the methods and the performance of the follower jammer in determining which frequency range to jam. The jammer circuit required for the frequency determination is not really a detector, the view point used in [2]. Neither is it an estimator, the view point used in [3]. It is most similar to a demodulator for M-ary NCFSK, but with differences. Since it would be confusing to call it a "demodulator", it was decided to call the circuit a "determinator".

There are waveform methods of mitigating the effects of follower jammers [4], [5], but these suffer from a few problems: more complex to implement (requires more synthesizers at the receiver), doesn't guarantee good performance, and are not useful if FDMA used.

In the following, emphasis will be on fast frequency hopping (one or more hops per information symbol). At the end, a short discussion will be given on slow frequency-hopping (more than one data bit per hop) performance.

FOLLOWER JAMMER CONFIGURATION AND GEOMETRICAL PROTECTION

The configuration for follower jammers is shown in Fig. 1. The transmitter to receiver distance is D_{tr}, the transmitter to jammer distance is D_{tj}, and the jammer to receiver distance is D_{jr}. At the follower jammer is a receiver plus a determinator circuit. The hop period is T_h which will be assumed $= 1/R_h$. The SNR at the determinator is E_{hf} / N_o where E_{hf} is the energy/hop at the jammer's receiver. At the authorized receiver, there is a SNR of E_{ht} / N_{or}, and an SJR to be discussed later. If the determinator correctly determines the frequency of the transmitted hop, then it can generate jamming in a small region around this frequency thereby negating the advantage of FH. It will be assumed here that the jammer has available fast frequency synthesizers that can switch to a new frequency in a time $\ll T_h$.

It has been pointed out in many places [3] that if

$$T_h \le \Delta T = \left(D_{tj} + D_{jr} - D_{tr}\right) / c \qquad (1)$$

where c is the velocity of light and ΔT is the differential delay, then the jamming signal arrives at the authorized receiver too late to jam the original hop— the receiver is processing the next hop. The jammer locations that obey (1) are outside of an ellipse given by

$$\frac{4\left(x - D_{tr}\right)^2}{\left(D_{tr} + cT_h\right)^2} + \frac{4y^2}{\left(D_{tr} + cT_h\right)^2 - D_{tr}{}^2} = 1 \qquad (2)$$

where the x and y axes are centered on the transmit antenna, and are illustrated in Fig. 1 along with a typical ellipse.

A two-dimensional representation is shown and is suitable for point-to-point communications over flat ground. For applications such as satcom, the results can be extended to three dimensions merely by revolving the ellipse about the x axis. For terrestrial communications, the three distances are of the same order of magnitude so that Fig. 1 is representative in scale. However, for satcom, $D_{tj} \ll D_{tr}$. For example $D_{tr} \approx 40{,}000$ km for a geo-synchronous satellite whereas D_{tj} would be no more than a few hundred km for airborne jammers, and even less for ground based jammers. As an example of the geometrical protection boundary for geo-synchronous satcom, the protection region is plotted in Fig. 2 for $R_h = 2000$, and 10000 hops/s.

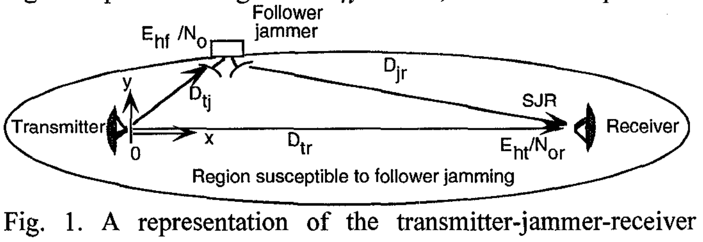

Fig. 1. A representation of the transmitter-jammer-receiver geometry.

WAVEFORMS CONSIDERED

For purposes of initial discussion, it is assumed that orthogonal M-ary NCFSK is used by the communicator, and fast hopping is used. Therefore, for each hop, there is a tone transmitted of duration T_h at one of M possible frequencies centered on the hop frequency. The tone spacing of the M bins is R_h for the minimum orthogonal spacing. Therefore, the unhopped user channel bandwidth is MR_h. If multiple access is required, such as in satcom, then it is assumed that FDMA is used with all users hopping with the same pattern but frequency offset from each other. The full hop bandwidth is W_{ss}. The hop spacing is assumed to be $\leq MR_h$.

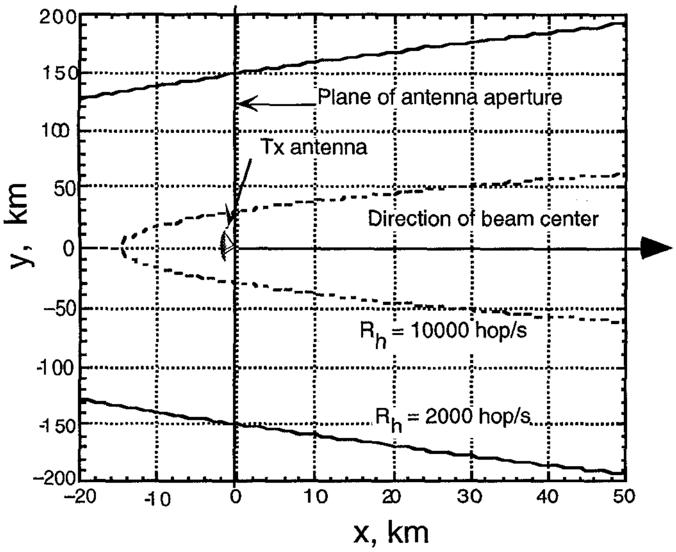

Fig. 2. Boundary lines for complete protection from follower jamming of a geo-synchronous satellite for two values of R_h.

DETERMINATOR DESCRIPTION

The jammer determinator divides the received spread band, W_{ss}, into N_b segments each of width

$$W = W_{ss} / N_b. \tag{3}$$

The jammer would like to determine which segment contains the frequency hop. The issue is, how can the jammer determine which segment contains the frequency hop. In [2], the classical energy detector is used for each segment which consists of a band-pass filter of width W, a square-law device and an integrator that integrates over a time T. They considered $T = T_h/2$, which meant that half a hop period was used just in determining the frequency. As a result, the geometrical protection is extended so that the equivalent hop period to be used in (1) becomes $T_h/2$, thereby improving the geometrical protection region. In [3], a frequency estimator is considered. Again, the time taken to do accurate estimation can be too long to achieve practical follower jamming.

The problem for the jammer is how to determine the hop bin in a time small compared to T_h. In contrast, the authorized receiver has the luxury of matched filtering which involves an integration over the whole hop period (symbol period), T_h. A follower jammer cannot wait that long. As discussed by Urkowitz [6] for detectors, when $TW \approx 1$, which is the condition pertaining here, then the "integration" becomes just taking a single sample. Then, the analysis cannot use the Gaussian approximations typically used in energy detectors, which usually have $TW \gg 1$. Since only a single sample is taken, the jammer will take it as soon after the start of the hop as possible. (It is assumed here that the jammer has some means of synchronizing to the start of the hop period. Such synchronization is relatively easy to implement.) For a realizable filter of width W, the output due to a pulse will rise to its maximum at a time about 1/W after the leading edge of the input pulse. Therefore, the best time for the jammer determinator to sample is at about

$$T_w = 1 / W \tag{4}$$

after the start of the hop.

The determinator circuit has a form such as shown in Fig. 3. It is assumed that the bandpass filters of width W are ideal brick wall filters. As pointed out in [6], it doesn't matter to the performance whether a square law or and true envelope detector is used. Therefore, we consider a true envelope detector since directly applicable analysis can be taken from the literature.

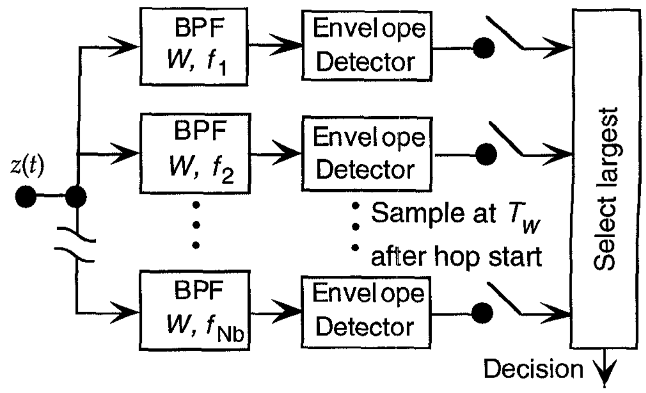

Fig. 3. A block diagram of the jammer's frequency bin determinator circuit.

ANALYSIS

The analysis is much the same as for analyzing the demodulation of M-ary non-coherent FSK. The derivation in [7, pp. 213-215] will be followed. First, the results of [7] are presented. Then, these results are recast to fit the circuit of Fig. 3.

The received signal at the jammer interceptor is

$$z(t) = \sqrt{2E_{hf} / T_h} \cos(\omega_i t + \alpha) + n(t)$$

$$\text{for } 0 \leq t \leq T_h, \; i = 1, 2, \ldots, N_b$$

where E_{hf} is the energy per symbol received at the follower jammer, ω_i is the radian frequency of the signal in the ith bin, T_s is the symbol period, α is random phase, and $n(t)$ is system noise with double sided power spectral density $N_o/2$. The demodulator discussed in [7] uses a bank of N_b matched filters and envelope detectors. The ith branch is implemented by first performing I and Q down conversion by multiplying the signal by $\sqrt{2/T_h}\cos(\omega_i t)$ and $\sqrt{2/T_h}\sin(\omega_i t)$, respectively. The result is integrated over the interval T_h, and each of the I and Q integrator outputs are sampled at T_h, and the envelope calculated. The largest is declared to be the bin in which the signal was sent. The probability of a correct determination of which of the N_b branches actually contains the transmitted signal is given by [7]

$$P_c = \int_0^{\infty} \left(1 - e^{-r^2/2}\right)^{N_b - 1} r e^{-\left(r^2 + 2E_h/N_o\right)/2} I_0\left(r\sqrt{\frac{2E_h}{N_o}}\right) dr \tag{5}$$

where $I_0(\bullet)$ is the modified Bessel function of order zero.

The steps in the above derivation for M-ary NCFSK are now recast to fit the determinator. First, the values of the signal squared at the bin containing the signal, and noise variance at all bins as seen at the sampler at the sampling instant (T_h for the demodulator and T_W for the determinator) were found for both systems and are listed in Table 1. Then, the corresponding output SNR for the determinator in Fig. 3 is found to be $E_s / \left(2WT_hN_o\right)$, which is somewhat less than the SNR obtained in the corresponding demodulator.

TABLE 1. Summary of SNR components for the demodulator and determinator.

	Demodulator	Determinator
signal squared	E_s	E_s / T_h
noise variance	$N_o / 2$	$2N_oW / T_h$
Output *SNR*	$2E_s / N_o$	$E_s / \left(2WT_hN_o\right)$

The probability of a correct determination of which of the N_b branches contains the hop is then found by appropriate modification of (5) to get

$$P_{hc} = \int_0^\infty \left(1 - e^{-r^2/2}\right)^{N_b - 1} re^{-\left(r^2 + E_{hf}/\left(2WT_hN_o\right)\right)/2} \bullet I_0\left(r\sqrt{\frac{E_{hf}}{2WT_hN_o}}\right)dr \tag{6}$$

This probability is dependent upon input *SNR*, W, T_h, and N_b. However, W and N_b are related by (3). It is found useful to define a form of normalized SNR as

$$g = E_{hf} / \left(WT_hN_o\right) \tag{7}$$

so that (6) becomes

$$P_{hc} = \int_0^\infty \left(1 - e^{-r^2/2}\right)^{N_b - 1} re^{-\left(r^2 + g/2\right)/2} I_0\left(r\sqrt{g/2}\right)dr \tag{8}$$

Values of P_{hc} were computed numerically as a function of g for 3 values of N_b and are plotted in Fig. 4. It is seen that they follow the "S" shape curve of the classical energy detectors with low values of $P_{hc} \approx 1 / N_b$ for small g, values close to 1 for large g, and a fairly rapid transition region between these two extremes. The relative effects of increasing g and N_b are seen. The improvement in detectability by increasing g is offset slightly by upward shift of the curves in Fig. 4 as N_b increases. As an example, for an increase of N_b from 100 to 1000 (10 dB increase), the curves at P_{hc} = 0.5 shifts to the right by < 2 dB. Since an increase of N_b by 10 dB also corresponds to an increase in g by 10 dB, the overall advantage to the determinator is >8 dB.

For effective follower jamming, a high value of P_{hc} is needed. Since the transition region from very poor to very good determinability is relatively small, the middle of the transition, is taken as the point of acceptable determination performance. At this point the determinator has obtained a P_{hc} of 0.5.

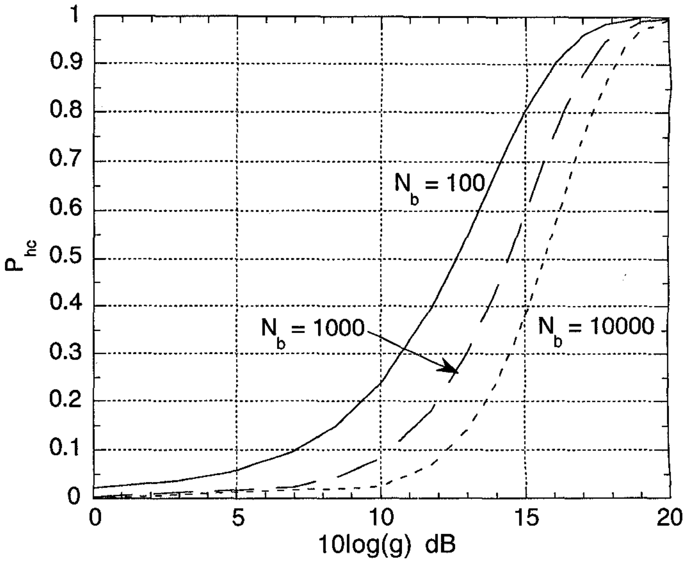

Fig. 4. A graph of P_{hc} as a function of g in dB for 3 values of N_b.

In order to find the middle of the transition, numerical analysis was performed on (8) to find pairs of values of N_b and g that result in P_{hc} = 0.5. The results are plotted in Fig. 5 with linear g against log(N_b). The range of values of N_b were from 10 to 10^4 with the idea that 10 represents the lowest amount of jamming gain that would be worthwhile, while 10^4 represents an upper practical range. It was noted that this plot was approximately a straight line for which an empirical relation was determined as

$$g = 9.61\log\left(N_b\right) - 0.99 \tag{9}$$

By equating (7) and (9), the SNR for P_{hc} =0.5 is found as

$$E_{hf} / N_o\Big|_{P_{hc}=0.5} = WT_h\left[9.61\log\left(N_b\right) - 0.99\right] \tag{10}$$

This SNR can be made a function of N_b only, by using (3) so that $WT_h = W_{ss} / \left(N_bR_h\right)$. If the FH processing gain, which was defined in [1] as

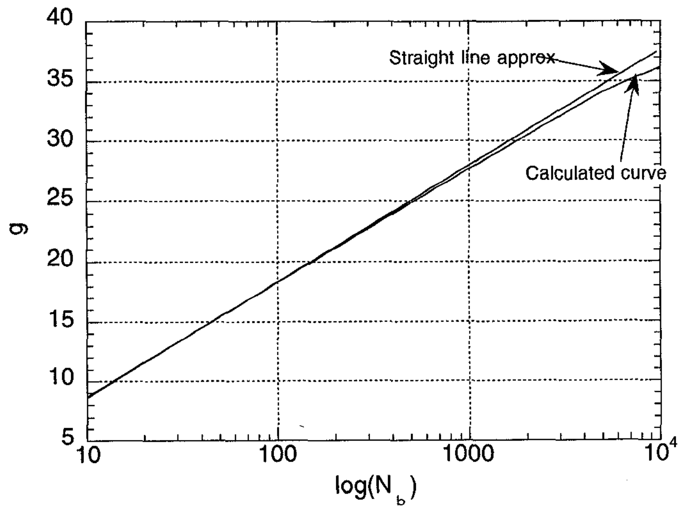

Fig. 5. A plot of the numerically computed value of g for P_{hc} = 0.5 as a function of log(N_b).

$$PG_{fh} = W_{ss} / R_h \tag{11}$$

is used, then (10) can be rewritten as

$$E_{hf} / N_o \big|_{P_{hc}=0.5} = \frac{PG_{fh}}{N_b} \left[9.61 \log(N_b) - 0.99 \right]. \tag{12}$$

The value of $E_{hf} / N_o \big|_{P_{hc}=0.5}$ was calculated and then plotted in Fig. 6 as a function of N_b for a number of values of PG_{fh}. As expected intuitively, the jammer's required SNR increases as PG_{fh} is increased. However, a surprise result is that the required SNR *decreases* as the N_b is increased. This result arises because the effect of N_b in (8)— the effect of the first factor in N_b is more than offset by the two factors in g which is proportional to N_b.

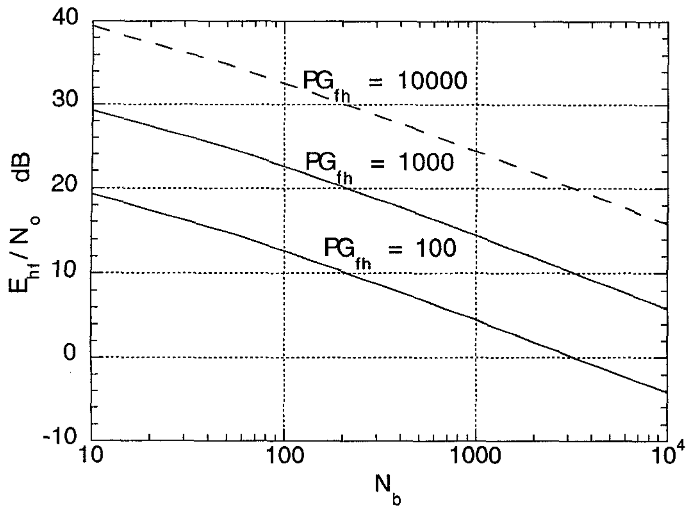

Fig. 6. A plot of $E_{hf} / N_o \big|_{P_{hc}=0.5}$ as a function on N_b for three values of PG_{fh}.

LINK BUDGET CONSIDERATIONS

It is seen that P_{hc} is dependent upon SNR received by the determinator, which in turn is dependent upon the transmitted power, the distance D_{tj}, the gain, G_{tj}, of the terminal antenna in the direction of the jammer, and the gain, G_{jt}, of the jammer in the direction of the transmitter. Obviously, the communicator should have as narrow a beam as possible to keep G_{tj} as small as possible.

Some idea of the levels of E_{hf} / N_o that would arise as affected by the various distances and gains can be obtained with a few simplifying assumptions. The transmitter transmits a power level that results in an E_{ht} / N_{or} at the authorized receiver that meets the specifications for the link, where N_{or} is the noise density at the reciever. The SNR at the follower jammer is then approximately

$$\frac{E_{hf}}{N_o} \approx \frac{E_{ht}}{N_{or}} \left(\frac{D_{tr}}{D_{tj}} \right)^{\alpha} \frac{G_{tj}}{G_{tr}} \tag{13}$$

where α is the propagation constant which is 2 for free space propagation, such as for satcom, and varies between about 2.5 up to about 4 for terrestrial propagation. Terrain shielding would be equivalent to making α even larger. The effect of (13) is a particular problem for satcom because the distance D_{tr} is so large. For example, for a geo-stationary satellite and a D_{tj} of 50 km, $20\log(D_{tr} / D_{tj}) = 58$ dB. This very large advantage will more than make up the large SNR required by the determinator such as given by the examples in Fig. 4. There would have to be considerable antenna protection to compensate.

In all the above, the determinator and jamming transmitter were co-located. It is possible that they could be separated so as to obtain a larger E_{hf} / N_o by being relatively close, yet not giving away its location when transmitting the jamming. The fact that there are now an extra delay in the jammer loop must be taken into account in the analysis.

JAMMING STRATEGY AND MULTIPLE ACCESS

The jammer's choice of W involves a number of tradeoffs between jamming efficiency, determinator performance, and complexity.

Once the determinator has decided in which segment of width W the hop is located, all the available jamming power is concentrated into a jamming band, W_j, centered on this determined band. However, the determinator only knows that there is an M-ary tone somewhere in the width W; it does not know which of M frequencies the user is using. The jammer wants to jam the entire channel width which is $\approx MR_h$ for fast hopping NCFSK. If W>>MR_h, then the jammer chooses $W_j = W$. The optimum jamming efficiency requires a determinator resolution of

$$W \approx MR_h / 2 \tag{14}$$

so that the smallest effective jamming width of $W_j = MR_h$ can be used. Therefore, from (3) and (14), the maximum number of bins that the jammer needs to determine for the most efficient jamming is

$$N_b \big|_{\max} = 2W_{ss} / (MR_h) \tag{15}$$

For cost reasons, the jammer would like to keep N_b as small as possible. For maximum jamming efficiency, N_b need be no larger than given by (15). Conversely, the value of N_b needed by the determinator for particular values of E_{hf} / N_o is defined by curves such as in Fig. 6, where, for a given PG_{fh}, the required SNR decreases as N_b increases. Under certain link budget conditions, the N_b required for good determinability can exceed that given by (15) for efficient jamming.

In satcom using multiple access with hopping FDMA, the follower jammer has an opportunity to jam all users based upon following just one user. The determinator determines the segment in which one user hop is located. If there are U users, the occupied user hopping band would have a width of UMR_h. To ensure jamming of all users, the jammer would have to jam over a width $2UMR_h$ centered on the determined frequency segment.

ERROR PERFORMANCE: FAST HOPPING

The probability of symbol error for noise follower jamming of fast hopping can now be derived. Because of the differential geometrical delay, ΔT, and the sampling delay T_w, only the final section, $T_h - (\Delta T + T_w)$, of the hop will be jammed, provided $T_h - (\Delta T + T_w) > 0$. Let the average total jamming power be J_{tot}. This jamming power is transmitted for time T_h, and is spread over the jamming band, W_j. Furthermore, the receiver integrates over T_h so that effective jamming power, on those hops correctly determined, is reduced by the factor $\left[T_h-\left(\Delta T+T_w\right)\right]/T_h$. Thus, the effective jamming noise power "density" as seen at the receiver is

$$J_{oe}=\left(J_{tot}/W_j\right)\left[T_h-\left(\Delta T+T_w\right)\right]/T_h \tag{16}$$

The signal-to-jammer ratio at the legitimate receiver on the jammed hops is then [1]

$$SJR_r=E_{ht}/J_{oe}\ . \tag{17}$$

Also, $SNR_r=E_{ht}/N_{or}$. Let the probability of symbol error as a function of SNR and SJR be $P_s(\bullet)$ which is given in the literature for various forms of modulation. Then the total error probability is

$$\begin{aligned}P_{stot}&=P_{hc}\bullet P_s\left(E_h/\left(J_{oe}+N_{or}\right)\right)\\&\quad+\left(1-P_{hc}\right)\bullet P_s\left(E_{ht}/N_{or}\right)\text{ for }T_h-\left(\Delta T+T_w\right)>0\\&\approx\left(1/N_b\right)\bullet P_s\left(E_h/\left(J_{oe}+N_{or}\right)\right)\\&\quad+P_s\left(E_{ht}/N_{or}\right)\text{ for }T_h-\left(\Delta T+T_w\right)<0\end{aligned} \tag{18}$$

An alternative jamming strategy is possible if the jammer can determine all three distances. Then, all the jamming power is concentrated into the last $T_h-\left(\Delta T+T_w\right)$ s of the jamming hop. The jamming density increases to become $J_{oe}=J_{tot}/W_j$, and the above equations for P_s would be modified accordingly. However, such a jammer would have to be quite sophisticated.

Similar results to the above can be derived for a jammer using tones instead of noise.

ERROR PERFORMANCE: SLOW HOPPING

If slow hopping is used, there will be multiple data symbols per hop. Here, the signal channel bandwidth increases and will be in the order of $R_s \approx 1/T_s$, depending upon the modulation type used, where, R_s and T_s are the symbol rate and period, respectively. The follower jammer must vary the determinator filter widths, W, accordingly. As before, from (3), $T_w \approx 1/W$. In the equations for the determinator performance, the E_{hf} used for fast hopping is replaced by $E_{sf}N_s$ where E_{sf} is the energy/symbol received by the follower jammer, and N_s is the number of data symbols per hop. Thus, the determinator enjoys an increased SNR over that for fast hopping.

Because of the differential geometrical delay, ΔT, and the sampling delay T_w, only the symbols in the final fraction, $\left[T_h-\left(\Delta T+T_w\right)\right]/T_h$, of the hop will be jammed. A simple approximation to the probability of bit error, P_b, can be obtained by assuming that the jammer has sufficient power to cause an bit-error probability of 0.5 in this fraction of the symbols. Then

$$\begin{aligned}P_b&\approx P_{hc}\left(0.5\left[T_h-\left(\Delta T+T_w\right)\right]/T_h\right)\text{ for }T_h-\left(\Delta T+T_w\right)>0\\&=0\quad\text{otherwise}\end{aligned} \tag{19}$$

The fact that these errors will come in bursts should be taken into account in any error correction coding considerations.

ANTI-FOLLOWER RECIPE

The anti-follower design procedures would then follow the following steps.

1. Designer starts with a trial hop rate, a given W_{ss}, modulation form, and expected geometry.
2. Use (2) to determine the absolute geometrical protection zone based upon $T_h-\Delta T<0$.
3. If jammers potentially inside the absolute geometrical protection zone, then proceed with the following steps.
4. Use (18) for fast hopping or (19) for slow hopping to estimate error performance for jammers inside the geometrical protection zone.
5. Based upon the value for T_w determined, calculate the effective geometrical protection zone based on $T_h-\left(\Delta T+T_w\right)<0$
6. Use (12) to determine the value of $E_{hf}/N_o\big|_{P_{hc}=0.5}$ needed by the determinator.
7. Apply user link budget values and geometrical values to (13) to determine if follower jammer can achieve sufficient $E_{hf}/N_o\big|_{P_{hc}=0.5}$.
8. Iterate as necessary.

The vulnerability analysis of existing systems is performed with just one iteration of the above.

CONCLUSION

The performance of the determinator needed by a follower jammer was described and analyzed, which led to a design recipe. The SNR required by the jammer determinator was found to be much higher than the SNR required by the authorized communications receiver. The determinator performance was seen to improve with increasing N_b. Conversely, it was seen that as PG_{fh} is increased (by either increasing W_{ss} or decreasing the data rate), the determinability performance of the jammer degrades. In general, it would appear that the follower threat can be reduced to tolerable levels by use of current practical hop rates.

ACKNOWLEDGMENT

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