Probability of intercept for frequency hop signals using search receivers (I)

This article is not only intended to brush up the reader's knowledge on the subject but also presents latest scientific findings. The probability of intercept for bursts and frequency hop signals by means of search receivers or scanning direction finders is calculated on a general basis and with particular attention to multichannel receivers and overlapping search and hop frequency ranges. The article also deals in detail with the timing of the receiver sequence coinciding with the hopper sequence*. For the sake of simplicity, ideal conditions are assumed.

1 Radiomonitoring equipment

Search receivers (FIG 1) can be tuned in rapid succession to different frequencies within a wide range and make an attempt to intercept at each one [1]. When detected signals are displayed in the time domain (eg waterfall display), a CW transmitter is characterized by its mean frequency, which is constant in time, and a frequency-hopping (FH) transmitter by its typical hop pattern.

Allocating detected frequencies to individual transmitters in dense scenarios is rather difficult because of the multitude of signals present, particularly when several FH transmitters are received in the same band. This task can be simplified by using a **scanning direction finder** (FIG 2) in such a way that the angle of arrival (AoA) of each signal detected by the search receiver of the direction finder is determined in addition with the aid of a DF antenna and a DF algorithm [2]. If the measured AoAs are displayed as a function of frequency, FH transmitters can be identified by their characteristic

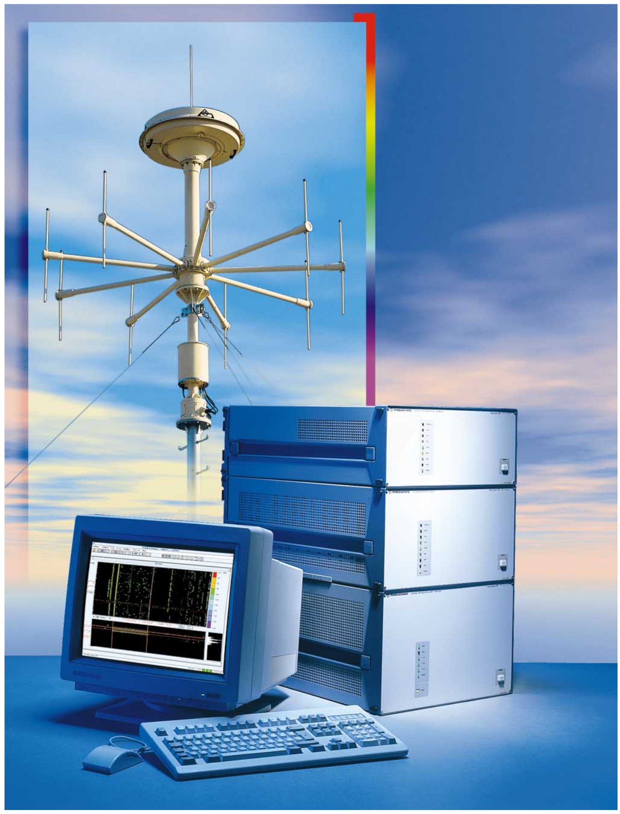


FIG 2
Digital Scanning Direction Finder DDF0xS for 0.5 to 1300 MHz
Photo 43 123

FIG 1
Search Receiver ESMA for VHF-UHF range
Photo 42 190

* A similar article by the same author was published in »Frequenz« 52 (1998) 7-8.

"string of pearls" along the direction of incidence (FIG 3).

For an FH transmitter to be detected with the aid of a search receiver or scanning direction finder, the hop sequence of the transmitter and the scan sequence of the receiver must coincide. Given a random hop sequence and a hop-independent receiver sequence, only the probability of intercept can be described. Reference [3] deals with this subject for single-channel search receivers. The article however merely considers the probability of at least one hit and does not give details on the dwell time of the search receiver at the instantaneous frequency position. By contrast, reference [4] only describes a special case of overlap of hop and search frequency ranges and does not go into the timing of the receiver sequence coinciding with the hopper sequence.

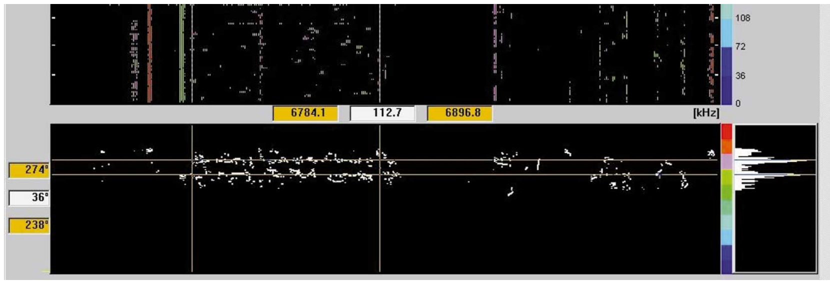


FIG 3 Detection of two FH transmitters near noise limit with Digital Scanning Direction Finder DDF01S in same frequency band 6784.1 to 6896.8 kHz marked by vertical cursor lines. In waterfall display (upper display window) two transmitters cannot be distinguished, in azimuth versus frequency display in lower window and azimuth histogram right it can be seen that two FH transmitter signals arrive with azimuth difference of 36°.

2 Presumptions

The behavior of a **hopper** is assumed to be random: the channels of the hop range (M_{FH}) are used in random sequence, the current channel being selected independently of all previously and subsequently selected channels. The probability of selection should be the same for all hop channels ($1/M_{FH}$), although there is no certainty of any channel appearing at all within a given period of time. The burst time (dwell time of the hopper on an emitted frequency) is T_h. In the case of variable hop times, T_h is the average value. For the sake of simplicity, regular, contiguous channel spacings are assumed for the frequency range. The frequency range occupied by the hopper is also taken as being free from any other signals.

It is further assumed that the **receiver** (monitoring receiver or DF receiver) systematically scans the defined frequency range with the same frequency spacing as used by the hopper. The center frequencies of the scanned channels (M_{Sc}) may come in any sequence, eg linear with time (linear staircase) or as a pseudo-random sequence. It must however be certain with all hop sequences that each of the selected M_{Sc} channels is used exactly once in a scan. In this case the random sequence is not a stochastic process like the hop sequence but a systematic search, even though with complex timing. A full number of complete scans is assumed to be performed each time. The duration of a scan corresponds to T_{Sc}. Irrespective of the type of scan, the probability of a receiver operating at a certain channel during a randomly chosen time is $1/M_{Sc}$ for each of the M_{Sc} channels.

Each frequency position of the receiver is assigned a dwell time T_d (FIG 4) consisting of the integration time T_i and a remaining period T_{Syn}. T_{Syn} contains the settling time of the receiver synthesizer and the time required for signal processing (eg with direction finders the time required to calculate a bearing):

$$T_{Syn} = T_d - T_i \qquad (1)$$

The integration time T_i depends on the settling time of the filters used. Signals with a duration of $T_h \leq T_i$ are considered not detectable, ie a signal must have a length of at least $T_h > T_i$ to be detected. The received bursts should have sufficient power to be detected when at least one integration time T_i falls within the burst interval T_h and the hop frequency and the receive frequency are identical. This is a very simple way of approaching the intercept procedure. In this consideration the relationship between the probability of a false alarm, intercept threshold, S/N ratio, averaging and probability of intercept is not taken into account. Therefore, the fact will also be ignored that, to obtain constant S/N ratio at the input of the detection device, field strength should be increased proportionally to $\sqrt{(1/T_i)}$ at short integration times T_i.

The frequency ranges of hopper and receiver should at least partially overlap by a number of channels

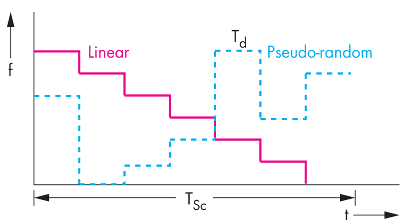


FIG 4 Search sequences of receiver

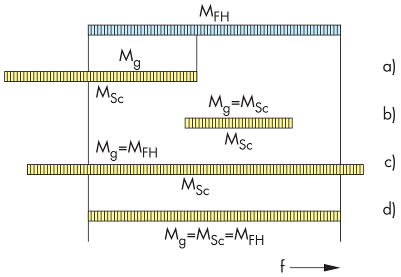


FIG 5 Frequency bands of hopper and receiver: a) general overlap; b) search range fully inside hop range; c) hop range fully inside search range; d) search range = hop range

M_g in the common frequency band (FIG 5).

With digital signal processing, receivers using parallel, identical filter/detector channels can be implemented (multichannel receiver), in the case of many channels by means of fast Fourier transform for instance. Whenever the receiver locks to a specific frequency, K filters/detectors are simultaneously active.

3 Probability of intercept for single bursts

The probability of intercept for single bursts of an FH transmitter will be examined first. The considerations are also valid for the detection of any single burst, ie of any signal with the length T_h that occurs only once within an extended observation period T_t.

3.1 Probability of intercept during single trial

As can be seen from FIG 5, the transmitter may use any of the M_{FH} channels, and the receiver be in any of the M_{Sc} channels, so $M_{FH} \times M_{Sc}$ combinations are possible. It is possible for both to meet in one of the M_g common channels. If the number M_g of a possible coincidence between the transmitter and receiver is related to the number of possible combinations, the probability of intercept for a single burst in a single trial is [3]:

$$P_1 = \frac{M_g}{M_{FH} M_{Sc}} \qquad (2)$$

The following applies to multichannel receivers. If K parallel filters with associated detectors are implemented in the receiver at channel spacing at each frequency position, the probability of hitting the burst in one of the K channels increases by the factor K compared with (2):

$$P_1 = \frac{M_g K}{M_{FH} M_{Sc}} \qquad (3)$$

This applies when the number of parallel receiver channels is less than the number of common hopper and receiver channels ($K < M_g$). In the case of $K \geq M_g$, K should be replaced by M_g in equation (3).

In the following cases, the use of a multichannel receiver is generally assumed. The relationships for a single-channel receiver are then obtained with $K = 1$.

The following special cases should be mentioned:

1. The frequency range of the hopper is greater than that of the receiver and covers the latter completely ($M_{FH} > M_{Sc}$) (FIG 5b). With $M_g = M_{Sc}$ the following is obtained from (3) for a multichannel receiver:

$$P_1 = \frac{K}{M_{FH}} \qquad (4)$$

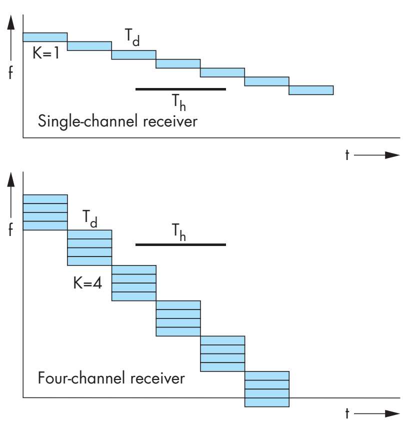


FIG 6 Search sequence of receiver and hop duration T_h (burst)

and for a single-channel receiver:

$$P_1 = \frac{1}{M_{FH}} \qquad (5)$$

The probability of intercept for a single burst in a single trial is independent of the total number of receiver channels M_{Sc} when the ranges overlap as shown in FIG 5b.

2. The frequency range of the receiver is greater than that of the hopper and covers the latter completely ($M_{Sc} > M_{FH}$) (FIG 5c). With $M_g = M_{Sc}$ the following is obtained from equation (3):

$$P_1 = \frac{K}{M_{Sc}} \qquad (6)$$

The possibility of performing irrelevant measurements outside the transmitter frequency range entails reduced probability of intercept for a single burst in a single trial as against (4) at a constant value of M_{FH}.

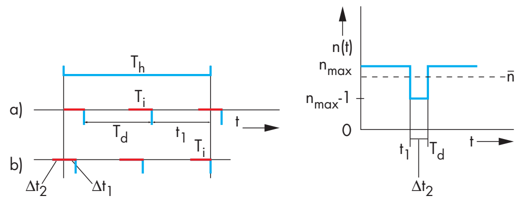
3.2 Several trials during single burst

More than one trial can be made with a scanning receiver during a burst when the dwell time of the receiver at a specific frequency position is sufficiently short in comparison with the burst duration (FIG 6). A number of n valid trials may be performed during consecutive dwell times T_d of the receiver within the burst period T_h. An intercept attempt is considered valid when the integration time is completely covered by the burst, ie if no frequency change or start and stop of a burst occurs during the integration time T_i of the detector. The number n depends on the timing of the burst T_h and the receiver dwell time T_d at a specific frequency position. The following applies for the mean number $\bar{n}$ of valid intercept attempts during the hop period T_h:

$$\bar{n} = \frac{T_h - T_i}{T_d} = \frac{T_h - T_i}{T_{Syn} + T_i} \qquad (7)$$

Derivation of equation (7)

The diagram left shows the hop interval T_h of the transmitter and part of the receiver sequence with the dwell time T_d and integration time T_i shifted in two ways (a and b) with respect to T_h. Part of the two-valued periodic function $n(t)$ is shown right in relation to the shift t of the receiver sequence with respect to the hop period; function $n(t)$ uses the dwell time T_d and describes the number of valid intercept attempts during the hop time.



Function $n(t)$ is obtained as follows. The maximum number of valid intercept attempts results at position a of the receiver sequence relative to the burst. Only one of the integration times T_i contains a frequency change or the end of a burst, so only one of the intercept attempts is invalid. The maximum number of valid intercept attempts is obtained as follows:

$$n_{max} = INT\left(\frac{T_h}{T_d}\right) \quad \text{where } INT(x) = \text{integer part of } x.$$

When the receiver sequence is shifted in the direction t, n_{max} remains unchanged until position b is reached, ie for the shift duration t_1. Shifting the receiver sequence in the direction t beyond position b will yield two invalid intercept attempts, so that only $n_{max}-1$ valid intercept attempts remain. This situation continues until the total shift corresponds to a period T_d and the receiver sequence arrives at position a again. Consequently $n(t) = n_{max}-1$ is maintained for the time Δt_2.

The arithmetic mean of $n(t)$ [3] stands for the average number of valid intercept attempts:

$$\bar{n} = \frac{1}{T_d}\int_0^{T_d} n(t)dt = \frac{n_{max} \times t_1 + (n_{max}-1) \times \Delta t_2}{T_d}$$

From $\Delta t_1 = T_h - n_{max} \times T_d$, $\Delta t_2 = T_i - \Delta t_1$ and $t_1 = T_d - T_i + \Delta t_1$ equation (7) is derived:

$$\bar{n} = \frac{n_{max}(T_d - T_i + T_h - n_{max}T_d) + (n_{max}-1)(T_i - T_h + n_{max}T_d)}{T_d} = \frac{T_h - T_i}{T_d}$$

The derivation of this equation is presented in the blue BOX.

During a search, each intercept attempt of the receiver is made at a different frequency position, so the probability of hitting the burst increases with each attempt beyond $n = 1$ during a burst period. The probability of intercepting a burst with $\bar{n}$ valid attempts within T_h is therefore defined by

$$P_{1h} = P_1 \times \bar{n} = \frac{M_g}{M_{FH} M_{Sc}} K \times \bar{n}$$

$$= \frac{M_g K}{M_{FH} M_{Sc}}\left(\frac{T_h - T_i}{T_d}\right) \qquad (8)$$

The validity of (8) has the following limitations:

a) A basic precondition is $T_h/T_i > 1$, ie a burst can only be detected if it is longer than the detection time.

b) The probability defined by (8) can theoretically be $P_{1h} > 1$ provided $(T_h - T_i)/T_d$ is long enough. However, with a long burst duration T_h, the highest intercept probability $P_{1\,hmax} \leq 1$ is reached when the search receiver is able to scan all M_{Sc} channels during one burst (burst time longer than complete scan, $T_h > T_{Sc}$). When T_h is further increased, the probability of intercept for a single burst does not rise above $P_{1\,hmax}$. $T_h > T_{Sc}$ yields $\bar{n} = M_{Sc}/K$ and thus the following limits apply to (8):

$$T_i < T_h \leq \left(\frac{M_{Sc}}{K} T_d + T_i\right) \qquad (9)$$

The maximum achievable probability of intercept in the case of long bursts depends on the degree of overlap of the hop range with the receiver scan range.

a) General case (FIG 5a):

$$P_{1\,hmax} = \frac{M_g}{M_{FH}} \qquad (10)$$

b) The hop range is completely covered by the scan range $M_{Sc} \geq M_{FH}$ (FIG 5c and d):

$$P_{1\,hmax} = 1 \qquad (11)$$

c) The scan range is completely within the hop range $M_{FH} \geq M_{Sc}$ (FIG 5b and d):

$$P_{1\,hmax} = \frac{M_{Sc}}{M_{FH}} \qquad (12)$$

A comparison of (8) and (3) shows that greater probability of intercept can only be reached at sufficiently high scan speeds:

$$\bar{n} \geq 1 \quad \text{for} \quad T_d + T_i \leq T_h \qquad (13)$$

If only the basic condition $T_i < T_h$ is met but not (13), it is possible that on average less than one valid intercept attempt can be made during a burst. In these cases the probability of intercept for a single burst is reduced according to (8) as against (3).

To be continued.

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Probability of intercept for frequency hop signals using search receivers (II)

3.3 Receiver in wait mode

Given that the hopper's frequency spacing is known from searching the frequency range, a receiver can be fixed tuned to one of the hop channels. The FH transmitter is then detected when its instantaneous frequency coincides with the set receive frequency. For a hop to be detectable its duration must be $T_h > T_i$. In wait mode (hopper trap) the time required for synthesizer setting and signal processing does not influence probability of intercept, so $T_d = T_i$ applies in this case.

Provided $T_i < T_h$ is valid and the condition described under 2 is met, exactly one detection occurs when the hop frequency and receive frequency coincide. On arrival of a burst the level threshold is exceeded as soon as the detection filter has settled, and at the end of the burst after a corresponding delay the level drops below the threshold again, allowing estimation of the burst duration. In this mode probability of intercept does not depend on hop duration T_h and the arrival time of the burst at the receiving antenna, as is the case with a search receiver in hop mode, so $\bar{n} = 1$ applies. FIG 5b with $M_g = M_{Sc} = 1$ and the equations (5) and (4) are valid for the probability of intercept of a single-channel and a multichannel receiver.

IIf the mean number of valid detection attempts per burst of a sufficiently fast search receiver is $\bar{n} > 1$, the probability of intercept is greater than in wait mode (equation 8). The probability of intercept in search mode may also be less than in wait mode however:

a) When the receiver scan is too slow compared with burst duration $(T_i < T_h < (T_d + T_i))$, in which case the factor $\bar{n} = (T_h - T_i)/T_d$ in (8) is less than 1.

b) If the search receiver is unable to use the a priori information on the hopper frequency range that was assumed for the receiver in wait mode, the receiver may also search in frequency ranges not used by the hopper (FIGs 5a and c). In this case the ratio M_g/M_{Sc} in (8) is less than 1 while in wait mode $M_g = M_{Sc} = 1$ holds.

4 Interception of frequency hoppers: repeated attempts

Up to now we dealt with the probability of intercepting a single hop (burst). If an FH transmitter can be observed for a certain operating time T_t (transmit time of hopper or total on time of receiver), the attempt to hit it can be repeated at N hops with

$$N = T_t \times f_H \qquad (14)$$

if f_H is the hop rate of the transmitter in frequency hops per time increment. (Note: f_H does not equal $1/T_h$ as synthesizer settling has to be considered for the transmitter too.) With each of the N attempts the probability of a hit is P, with $P = P_1$ in (3 to 6) or P_{1h} in (8).

4.1 Binomial distribution

The probability P_N that in N attempts a number Z of exactly k hits occurs is calculated according to the binomial distribution [5]:

$$P_N\,(Z = k) = \binom{N}{k} P^k\,(1-P)^{N-k}$$

$$\text{with } \binom{N}{k} = \frac{N!}{k!(N-k)!} \qquad (15)$$

and the mean value (mean number of hits)

$$\bar{k} = N \times P \qquad (16)$$

Of particular interest are the probabilities derived from (15) that the number Z of hits occurs within a defined interval:

a) The probability of at least one hit in N attempts is

$$P_N\,(Z \geq 1) = 1 - (1-P)^N \qquad (17)$$

b) The probability of k_1 to k_2 hits in N attempts is

$$P_N\,(k_1 \leq Z \leq k_2)$$

$$= \sum_{l=k_1}^{k_2} \binom{N}{l} P^l (1-P)^{N-l} \qquad (18)$$

c) The probability of at least k hits in N attempts is

$$P_N\,(Z \geq k) = \sum_{l=k}^{N} \binom{N}{l} P^l (1-P)^{N-l}$$

$$= 1 - \sum_{l=0}^{k-1} \binom{N}{l} P^l (1-P)^{N-l} \qquad (19)$$

4.2 Poisson theorem

With a large number of hopper channels M_{FH}, the probability P of intercept for a single hop is often very low, so that even with a large number N of attempts the product $N \times P$ is not a very high number but of the order of 1. In this case the binomial distribution (15) for k of the order of $N \times P$ may be approximated by the Poisson distribution [5]:

$$P_N\,(Z = k) \approx \frac{e^{-NP}(NP)^k}{k!} \qquad (20)$$

A special case should be mentioned: Given a large number of hopper channels M_{FH} and the search range of a single-channel receiver coinciding with the hop range of the transmitter

($M_{Sc} = M_{FH}$, FIG 5d), L complete scans are to be performed [4]. The receiver is to be able to perform on average just one valid detection attempt per frequency hop of the transmitter ($\bar{n} = 1$). With (5) the detection probability for a single burst is $P = P_1 = 1/M_{FH}$ and the total number of attempts $N = L \times M_{FH}$. With $N \times P = L \times M_{FH} \times (1/M_{FH}) = L$ and using (19) and (20), the probability of at least k hits (FIG 7) is

$$P_N(Z \geq k) = 1 - \sum_{l=0}^{k-1} P_N(Z = l)$$

$$\approx 1 - e^{-L} \sum_{l=0}^{k-1} \frac{L^l}{l!} \qquad (21)$$

According to (21) at least one hit occurs (trace $k = 1$ in FIG 7) with the probability

$$P_N(Z \geq 1) = 1 - e^{-L} \qquad (22)$$

4.3 DeMoivre-Laplace theorem

If the number N of attempts is sufficiently large that

$$NP(1 - P) >> 1 \qquad (23)$$

is obtained, the binomial distribution (15) can be approximated by a Gaussian distribution [5]:

$$P_N(Z = k) \approx \frac{e^{-(k-NP)^2/2NP(1-P)}}{\sqrt{2\pi NP(1-P)}} \qquad (24)$$

For the total probability (18) the following is obtained:

$$P_N(k_1 \leq Z \leq k_2)$$

$$\approx \frac{1}{2}\left[erf\left(\frac{k_2 - NP}{\sqrt{2NP(1-P)}}\right) - erf\left(\frac{k_1 - NP}{\sqrt{2NP(1-P)}}\right)\right] \qquad (25)$$

$$\text{where} \quad erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2}\, dy \qquad (26)$$

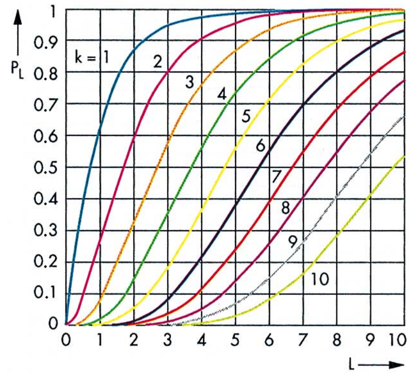

FIG 7 Probability P_L of at least k hits in L scans

Based on (25) with (19), the probability of at least k hits in N attempts is

$$P_N(Z \geq k)$$

$$\approx \frac{1}{2}\left[erf\left(\frac{N - NP}{\sqrt{2NP(1-P)}}\right) - erf\left(\frac{k - NP}{\sqrt{2NP(1-P)}}\right)\right]$$

$$\approx \frac{1}{2}\left[1 - erf\left(\frac{k - NP}{\sqrt{2NP(1-P)}}\right)\right] \qquad (27)$$

The relationship between the number of attempts and receiver scans is shown in the blue BOX.

5 Example

Let us assume that the search range of the receiver and the frequency range of the FH transmitter coincide (FIG 5d) and that the hopper and receiver have 2000 hop positions each ($M_{FH} = M_{Sc} = 2000$). In this case the probability of intercepting a single burst in a single measurement with a single-channel receiver is $P_1 = 1/M_{FH} = 1/2000$ according to (5).

a) Poisson theorem:
With L = 3 the probability of the hopper being intercepted at least once in three scans is 95% according to curve $k = 1$

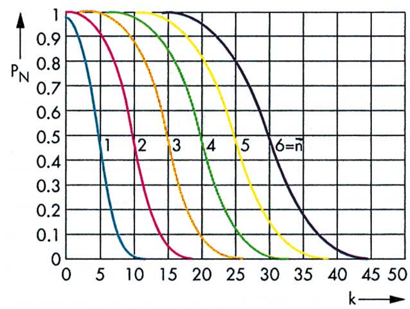

FIG 8 Single-channel receiver: probability P_N of at least k hits in $N = 10^4$ repeated attempts with mean number $\bar{n}$ of valid intercept attempts during one hop interval

Number of repeated attempts during a number of receiver scans

The number N of repeated attempts to detect a transmitter with a random distribution of frequency hops is a decisive parameter for determining probability of intercept (15) to (27). The relationship between N and the number L of receiver scans is as follows:

The dwell time of the receiver at a frequency is assumed to be T_d. For a systematic search through all frequency positions M_{Sc} of a single-channel receiver, the time $T_{Sc,1} = M_{Sc} T_d$ is required for one scan.

With (14) the number N of attempts during L scans is defined as $N_{L,1} = M_{Sc} T_d f_H L$.

In the case of a multichannel receiver with K parallel channels the scan time reduces to

$$T_{Sc,K} = \frac{M_{Sc} T_d}{K}$$

with the result that during L scans only

$$N_{L,K} = \frac{M_{Sc} T_d f_H L}{K}$$

attempts can be made. Seeing as the probability of intercepting a single hop with a multichannel receiver is higher by the factor K than that of a single-channel receiver (3, 8), the mean number $\bar{k}$ of hits is the same for the single-channel and the multichannel receiver for the same number L of scans. The observation time required by the multichannel receiver is shorter by the factor $1/K$.

in FIG 8 or (22), assuming that the receiver performs an average of one valid detection attempt per transmitter hop [4].

b) De Moivre-Laplace theorem:
Let the operating time T_t be sufficiently long that, according to (14), $N = 10^4$ is obtained for the number of repeated attempts. With (16, 8 and 7) the mean number of hits is then

$$\bar{k} = N \times P_{1h} = 10000 \times \bar{n}/2000$$
$$= 5 \times \bar{n}, \text{ where } \bar{n} = (T_h - T_i)/T_d$$

The probability of at least k hits can be approximated using (27). This is shown in FIG 8 for a single-channel receiver and a variable mean number $\bar{n}$ of valid attempts by the receiver during the hop interval T_h (ie with different scan speeds). Trace $\bar{n} = 1$ also applies to a single-channel receiver in wait mode. The same relationship for an eight-channel receiver is plotted in FIG 9. Here the mean number of hits according to (16) with $P = P_{1h}$ (8) is greater by a factor of 8 compared to a single-channel receiver. Trace $\bar{n} = 1$ is also valid for an eight-channel receiver in wait mode. In FIG 10 only one valid detection attempt is assumed per hop interval ($\bar{n} = 1$, $(T_h - T_i)/T_d = 1$ or wait mode) and the effect of an increased number of parallel receiver channels is shown.

For the probabilities of intercept calculated with (27) and shown in FIGs 8 to 10, the effect of a specific measure (parallel channels, faster scan) can easily be estimated with the aid of the mean number of hits according to (16):

The probability traces $P_N(k)$ reach a value of 0.5 when the minimum achievable number of hits is just equal to the mean number of hits ($k = \bar{k}$). With increasing values of $\bar{k}$ the traces consequently shift proportionally to the greater minimum number of hits. Taking a K-channel receiver and substituting (8) in (16), the mean number of hits for the coincidence of search and hop frequency range assumed in FIG 5d is given by

$$\bar{k} = N \times P_{1h} = N \frac{K \bar{n}}{M_{FH}}$$
$$= N \frac{K}{M_{FH}} \left(\frac{T_h - T_i}{T_d} \right) \qquad (28)$$

c) Binomial distribution:
If the same relationship as in FIG 10 is to be determined for just a small number of attempts, the binomial distribution must be used without approximations. The diagram shown in FIG 11 is obtained with (19) for only ten repeated attempts. The POI is correspondingly low.

6 Conclusion

Under the conditions described in section 2, the probability of intercept for a single burst (hop) is proportional to the product of the channel number K and the mean number $\bar{n}$ of attempts of a receiver in the hop interval T_h (8, 28). The measures "multichannel receiver" and "fast scan" have the same effect on probability of intercept and are therefore interchangeable. Both measures for increasing probability of intercept require more effort at the receiver end. A search receiver optimized for intercepting sufficiently strong signals works with the largest possible number K of parallel channels and a minimum dwell time T_d, ie the shortest possible times for detection, synthesizer settling and signal processing. Short intercept times call for broadband filters. When the detection time T_i is shortened, probability of intercept is limited by reduced selectivity to narrowband adjacent-channel signals and broadband interfering signals. If the interfering signal is broadband noise, the required field strength increases proportionally to $\sqrt{(1/T_i)}$ for faster detection time T_i. If the FH signal can be observed over a specific operating time, the attempts at detection can be repeated and thus the number of hits increased.

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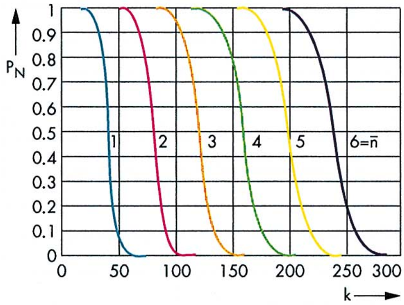

FIG 9 Eight-channel receiver: probability P_N of at least k hits in $N = 10^4$ repeated attempts with mean number $\bar{n}$ of valid intercept attempts during one hop interval

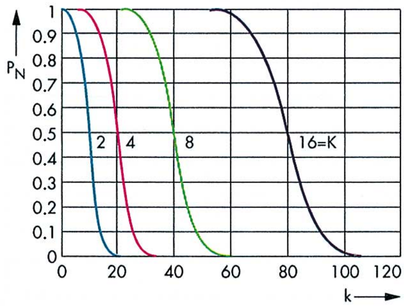

FIG 10 Receiver with K parallel channels, $\bar{n} = 1$: probability P_N of at least k hits in $N = 10^4$ repeated attempts

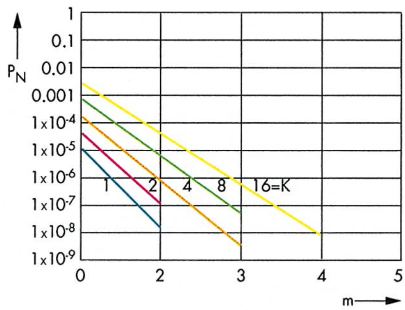

FIG 11 Receiver with K parallel channels, $\bar{n} = 1$: probability P_N of at least m hits in $N = 10$ repeated attempts

REFERENCES

[5] Papoulis, A.: Probability, Random Variables and Stochastic Processes. McGraw-Hill (1965), Chap. 3