Description of the Noise Performance of Amplifiers and Receiving Systems

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I. Introduction

IN GENERAL the output noise of a receiving system contains components contributed not only by the termination at the input of the receiving system but also by the receiving system itself. Furthermore, the output signal-to-noise ratio[1] of the system will depend not only on the output noise but also on the nature of the signal that is impressed upon the input of the receiver. Hence, any meaningful evaluation of the noise performance of a receiver when used in a particular system must include considerations of the sources that contribute to the output noise, the bandwidth and gain of the receiving system in all of its responses, the nature of the signal and the efficacy of the output utilization circuit. *It is evident that no single number can describe completely how well a given receiver will perform in all kinds of systems.*

What, then, are the pertinent attributes of a receiver, and how are they measured and quoted? From the viewpoint of the designer of the receiver, the attributes must be readily measurable. From the viewpoint of the designer of the system, the numbers quoted by the receiver designer must be such that the output signal-to-noise-ratio (SNR) under operating conditions can be calculated.

It is the responsibility of the designer of the system to match his signal to the bandwidth of the receiver and to know what penalty is paid when he doesn't. In general matching presents no hardship, since appropriate matching filters, which tend to optimize the output SNR, can always be introduced into the system. It is also the responsibility of the system designer to employ the best possible utilization circuit at the output of the receiver. The nature of the utilization circuit will depend upon the nature of the signal, whether it is AM, FM, single sideband, double sideband, sky noise, etc.

Let us assume that the system designer has considered carefully these important problems, that he has matched the noise bandwidth to his signal bandwidth and is using the most efficient detection for his signal. What else must he know about a given receiver to predict its noise performance? He must know the gain-frequency characteristics of the receiver. Does it have only one response or multiple responses? He must know how much of the output noise is attributable to the receiver itself. Thus the pertinent attributes that should be measured and quoted by the designer of the receiver are:

1) The gain at each of the responses,

2) The bandwidth,

3) The *effective input noise temperature.*[2]

The effective input noise temperature of the receiving system can be used with an input termination noise temperature such as antenna temperature to compute an *operating noise temperature*,[2] T_{op}, which is a system characteristic and is a function of the signal and the environment, etc. The operating noise temperature is a simple number for the designer of the system to use in

[1] We use the signal-to-noise power ratio as a measure of quality of the output response. This is reasonable in amplifiers or systems that we define as having a single output response, namely systems in which any frequency component entering the system at any one of the input frequencies produces a response at one single corresponding output frequency. An example of a case we do not intend to cover is the double-sideband degenerate parametric amplifier.

[2] IRE standard definitions of these italicized terms may be found in the preceding Standard.

evaluating his system noise performance, since kT_{op} is the power per unit signal output bandwidth required of an input signal to make the output SNR unity.

The terms operating noise temperature and effective input noise temperature have been defined but the concepts require further discussion. The relationship between operating noise temperature, *noise temperature*[3] of the input termination, effective input noise temperature and *noise factor*[3] will be brought out during the discussion.

The discussion here will deal with systems having single as well as multiple input responses, but only a single output response. A system with multiple input responses and a single output response is one in which several different input frequencies in the different input bands produce an output at one single output frequency in the output band.[4]

II. Operating Noise Temperature

The noise performance of a particular system may be evaluated in terms of its output SNR *under operating conditions.* Now the output signal power per unit bandwidth S_o can always be expressed as a signal power per unit output bandwidth, S_i, available at the input terminals multiplied by the signal gain G_s. The signal gain is defined (see definition of operating noise temperature) as the ratio of

1) the signal power delivered at the specified output frequency into the output circuit (under operating conditions) to
2) the signal power available at the corresponding input frequency or frequencies to the system (under operating conditions) at its accessible input terminations.

Stated in another way, S_i may be thought of as the output signal power per unit bandwidth referred to the input. In a similar manner, the output noise power per unit output signal bandwidth, N_o, can be referred to the input by dividing by G_s and can then be related to the *operating noise temperature*,[5] T_{op}, as follows:

$$\frac{N_o}{G_s} = kT_{op} \tag{1}$$

[3] IRE standard definitions of these italicized terms may be found in "IRE Standards on Electron Tubes: Definitions of Terms, 1957, 57 IRE 7.S2," Proc. IRE, vol. 45, pp. 983–1010; July, 1957. For convenience, these standard definitions are included as the Appendix to this paper.

[4] A parametric amplifier is an example where inputs at the so-called signal and idler frequency produce an output at the signal frequency.

[5] The use of temperature to express noise powers is particularly convenient when the noise powers are small and when the frequencies are in the normal frequency region, say up to 10^3 kMc. At these frequencies, the available output noise power per unit bandwidth from a resistor may be expressed as $P_n = kT$, where k is Boltzmann's constant, and T is the absolute temperature of the resistor. The use of temperature as a measure of receiving system noise does not infer that the sources of noise are necessarily thermal; only that the output noise power can be accounted for by a noiseless receiver with an input termination at a specified temperature.

Hence, the output SNR is

$$\frac{S_o}{N_o} = \frac{S_o/G_s}{N_o/G_s} = \frac{S_i}{kT_{op}}.$$

From this, it is clear that two receiving systems will exhibit the same output SNR if they have the same S_i/T_{op} ratio; also, that two receiving systems having the same available input signal power per unit output bandwidth must have the same operating noise temperature to produce the same SNR at the output.

III. Derivation of General Equation for Output Noise Power

We shall now derive the general expression for the noise power per unit bandwidth flowing into the output termination of a linear multiport transducer (see Fig. 1). This output noise power, at a specified output frequency, arises from two sources:

1) The contributions to the output noise power due to noise power available from the impedance terminations that are connected to all accessible ports except the output port under operating conditions. These contributions can be described by assigning appropriate noise temperatures to the input terminations at all of the various responses.
2) All other contributions to the output noise power. These include noise generated within the receiver components as well as noise resulting from any frequency conversions internal to the receiving system. Noise generated in the load and reflected at the receiver output may also contribute to this output noise power.

If we denote the portion of the output noise power per unit bandwidth described under 1) by N_{io} and that described under 2) by N_N, we can write the total output noise power per unit bandwidth N_o as

$$N_o = N_{io} + N_N. \tag{2}$$

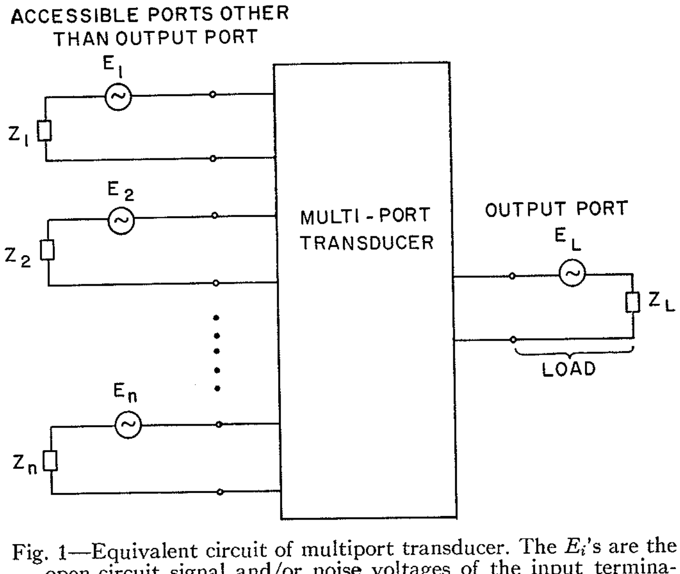

Fig. 1—Equivalent circuit of multiport transducer. The E_i's are the open-circuit signal and/or noise voltages of the input terminations. E_L is the open-circuit noise voltage of the load.

If T_{in} is the noise temperature at the nth response, and there is no correlation between the noises at different responses, then

$$N_{io} = k(T_{i1}G_{12} + T_{i2}G + \cdots + T_{in}G_n) \quad (3)$$

where G_n is the transducer gain of the nth response and is the ratio of 1) the output power delivered to the utilization circuit at the specified output frequency to 2) the corresponding input power available at the nth input response.

In a similar manner, we can express the noise attributable to the receiver in terms of the effective input noise temperature, T_e, which *by definition* is common to all responses. Thus

$$N_N = kT_e(G_1 + G_2 + \cdots + G_n) + N_L. \quad (4)$$

Here, N_L is a term that takes into account the contribution of the noise generated in the load and reflected at the output of the receiver, since the effective input noise temperature definition does not include such a contribution. In order to evaluate N_L one must know the impedance and the equivalent noise temperature of the load, and the output impedance of the receiver. In most cases, N_L will be negligible compared to the other terms in this expression. The contribution N_L may be of importance in systems with insufficient gain, or in systems with an output impedance with a negative real part. In such cases, N_o of (2) is to be interpreted as the net noise power passing the cross section of the output port.[6]

A few words of explanation may be in order for the reason why T_e excludes the load noise contribution and T_{op} includes it. In excluding the load noise from the definition of T_e the effective input noise temperature of a single response two-port is brought into direct correspondence with its noise figure F according to the formula $T_e = 290\ (F-1)$. The noise figure cascading formula of single response two-ports may thus be adapted to T_e. The cascading formula facilitates the evaluation of T_e of an amplifier chain. The operating noise temperature T_{op} is intended to be a measure of the noise of a receiving system. The inclusion in T_{op} of the contribution of the load-noise gives a more realistic measure of system noise performance in those cases in which the load noise is appreciable.

Henceforth, we shall disregard N_L, because in most cases of interest it is negligible.

The total output noise power per unit bandwidth is then

$$N_o = k[G_1(T_{i1} + T_e) + G_2(T_{i2} + T_e) + \cdots + G_n(T_{in} + T_e)]. \quad (5)$$

[6] If complex Fourier transforms v of the voltage and i of the current can be defined, the net output power is

$$\frac{1}{2}\,\mathrm{Re}\int_{\omega_1}^{\omega_2} v^* i\,d\omega.$$

We can now characterize the noise performance of the receiving system in terms of the operating noise temperature T_{op} which, from (1), is given by

$$T_{op} = \frac{N_o}{kG_s}. \quad (6)$$

T_{op} may be seen to be a number which characterizes the noise performance of a receiving system under operating conditions. From a knowledge of T_{op}, one may compute the required input signal power to give a desired SNR at the output.

We must now show that the quantities in (6) can be readily measured and then apply these equations to various practical systems.

IV. Measurement of Parameters

In the discussion so far, the terms effective input noise temperature and operating noise temperature have been used, and these are defined for noise power per unit bandwidth at a specified output frequency. In practice, however, finite bandwidths are employed, and the average noise power per unit bandwidth in a specified output band is a more meaningful quantity. The latter term can be referred to the input and related to a temperature in a similar manner as was done for noise power per unit bandwidth at a specified output frequency. The equivalent temperature is then defined as the *average effective input noise temperature* $\overline{T}_e^2$.

The measurement of both bandwidth and gain are covered in most standard references. One must remember that both are in terms of power, not voltage. For the multiple-response receiver, the input bandwidth must be referred to.

It is of fundamental importance to establish clearly how the temperature, $\overline{T}_e$, which characterizes the noise performance of the receiver, can be determined by measurement. Since most modern noise generators used in noise measurements (noise diodes, gas discharge lamps, hot and cold loads) generate broad-band noise with constant amplitude across the band the direct measurement method is one in which noise is injected *equally* into *all* responses. In other words, the measurement conditions are usually such that the noise temperatures of all the input terminations are equal, such that

$$T_i = T_{i1} = T_{i2} \cdots = T_{in}. \quad (7)$$

Hence, if such a broad-band noise generator is connected to the input terminals of the receiver, the expression for the total noise power is

$$N_{To} = k(T_i + \overline{T}_e)(B_1G_{01} + B_2G_{02} + \cdots + B_nG_{0n}) \quad (8)$$

where B_n is the *noise bandwidth* and G_{0n} is the transducer gain at the reference frequency f_{0n} of the nth response.[7]

[7] For a discussion of these quantities see "IRE Standard on Methods of Measuring Noise in Linear Two Ports, 1959, 59 IRE 20 S1," Proc. IRE, vol. 48, pp. 61–68; January, 1960.

For a limiting bandwidth B_N common to all responses, (8) becomes

$$N_{To} = kB_N(T_i + \overline{T}_e)(G_{01} + G_{02} + \cdots + G_{0n}). \quad (9)$$

To measure $\overline{T}_e$, the output noise powers for two different temperatures of the input terminations T_i (hot) and T_i (cold) are observed. One defines a quantity Y by

$$Y = \frac{N_{To}\,(\text{hot})}{N_{To}\,(\text{cold})}. \quad (10)$$

From (9) one finds

$$Y = \frac{T_i\,(\text{hot}) + \overline{T}_e}{T_i\,(\text{cold}) + \overline{T}_e}. \quad (11)$$

Solving for $\overline{T}_e$ one has

$$\overline{T}_e = \frac{T_i\,(\text{hot}) - YT_i\,(\text{cold})}{Y - 1} \quad (12)$$

and, hence, one can compute the *average effective input noise temperature* of the receiver from the calculated value of Y and the known values of the two different input termination noise temperatures.

It is clear that if the noise generator terminates all receiver input responses and if the gain at each of the responses remains the same between the two measurements of N_{To} (hot) and N_{To} (cold), $\overline{T}_e$ may be computed directly from the two measurements without concern for the response characteristic of the receiver. It should also be pointed out that T_i (hot) and T_i (cold) may be actual (physical) temperatures if hot and cold bodies are used for the measurement, or may be the noise temperatures of gas discharge lamps or noise diodes. (The noise temperature is the temperature of a passive system having an available noise power per unit bandwidth equal to that of the actual generator employed.) The *effective input noise temperature*, T_e, which is defined at a specific output frequency, can be determined by including a filter between the receiver output and the power measuring device. The bandwidth of the filter must be sufficiently narrow so that the receiver characteristics, such as gain, noise, are constant over the band. If T_e of the receiver depends on the impedance and the noise temperature of the output termination at frequencies other than the specified output frequency, care must be taken that the insertion of the filter does not change T_e. When the spot frequency is near the center of the passband of the receiver, the temperature so obtained may not differ greatly from the average.

V. Calculation of T_{op} for Specific Systems

The expression for the operating noise temperature T_{op} was given in (6). Again, in practice, the noise performance of a receiving system will be characterized by an *average operating noise temperature*,[1] $\overline{T}_{op}$, which for the simple case of a square response with uniform gain G_s can be written as

$$\overline{T}_{op} = \frac{N_{To}}{kB_oG_s} \quad (13)$$

where B_o is the output signal bandwidth.[8] If B_N is common to all responses, the total output noise power is given in general by

$$N_{To} = kB_N[G_1(\overline{T}_{i1} + \overline{T}_e) + G_2(\overline{T}_{i2} + \overline{T}_e) + \cdots + G_n(\overline{T}_{in} + \overline{T}_e)] \quad (14)$$

where $\overline{T}_{in}$ is the averaged noise temperature and G_n is the transducer gain for the nth input response.

A. Single Response Receiver[9]

A simple case to consider is that in which the receiver has only a single response. In this case, all G's in (14) except the first are zero, and $G_1 = G_s$. Then

$$N_{To} = kB_NG_s(\overline{T}_{i1} + \overline{T}_e) \quad (15)$$

and so

$$\overline{T}_{op} = \frac{B_N}{B_o}(\overline{T}_{i1} + \overline{T}_e). \quad (16)$$

The bandwidth ratio, B_N/B_o, is equal to or greater than unity. The lowest operating noise temperature occurs when the noise bandwidth, B_N, matches the signal bandwidth, B_o. It is convenient to assume that the system designer will take care of this in his system design and so (15) becomes

$$\overline{T}_{op} = \overline{T}_{i1} + \overline{T}_e.$$

B. Multiple Response Receivers; Signal Input at One Response Only

For the case where the input signal occupies only response number 1, $G_s = G_1$, and, from (13) and (14), the expression for the average operating noise temperature becomes

$$\overline{T}_{op} = (\overline{T}_{i1} + \overline{T}_e) + \frac{G_2}{G_1}(\overline{T}_{i2} + \overline{T}_e) + \frac{G_3}{G_1}(\overline{T}_{i3} + \overline{T}_e) + \cdots + \frac{G_n}{G_1}(\overline{T}_{in} + \overline{T}_e) \quad (17)$$

where it has been assumed that the noise bandwidth is matched to the signal bandwidth.

[8] B_o is the bandwidth of the signal delivered to the output utilization circuit. (In the case of several coherent output signal responses—appearing in different frequency bands—B_o denotes the bandwidth of the signal in any one response. In the case of a superheterodyne receiving system, B_o denotes the signal bandwidth appearing in the intermediate frequency amplifier.)

[9] By single response receiver is meant any receiver in which only one frequency at the accessible input terminals corresponds to a single output frequency, regardless of the complexity of the gain-frequency characteristics.

For the special case in which, under operating conditions, the noise temperatures of the input terminations at all input responses are equal, (17) reduces to

$$\overline{T}_{op} = (\overline{T}_i + \overline{T}_e)\left(1 + \frac{G_2}{G_1} + \cdots + \frac{G_n}{G_1}\right). \qquad (18)$$

C. Multiple Response Receivers, Signal Input at More Than One Response

If we now wish to evaluate $\overline{T}_{op}$ for the case in which the received input signal is distributed over more than one input response, we note that only G_s can be affected in the equation

$$\overline{T}_{op} = \frac{N_{To}}{kB_oG_s}.$$

N_{To} is, of course, unaffected in a linear system and we assume that B_o, the signal output bandwidth, remains unaffected also.

When the portions of the input signal that are received by the various responses are totally *uncorrelated*, with their powers denoted by $S_{i1}, S_{i2}, \cdots, S_{in}$,

$$S_o = S_iG_s = S_{i1}G_1 + S_{i2}G_2 + \cdots + S_{in}G_n \qquad (19)$$

or

$$G_s = \frac{S_{i1}G_1 + S_{i2}G_2 + \cdots + S_{in}G_n}{S_{i1} + S_{i2} + \cdots + S_{in}} = \frac{S_o}{S_i}.$$

We again obtain $\overline{T}_{op}$ from (13) and (14) by substituting G_s:

$$\overline{T}_{op} = \frac{N_{To}}{kB_oG_s} = \frac{B_N[G_1(\overline{T}_{i1} + \overline{T}_e) + G_2(\overline{T}_{i2} + \overline{T}_e) + \cdots + G_n(\overline{T}_{in} + \overline{T}_e)]}{B_v\left[\dfrac{S_{i1}G_1 + S_{i2}G_2 + \cdots + S_{in}G_n}{S_{i1} + S_{i2} + \cdots + S_{in}}\right]}. \qquad (20)$$

For the simple case where $S_{i1} = S_{i2} = \cdots = S_{in}$, we obtain $G_s = (G_1 + G_2 + \cdots G_n)/n$, and with $B_N = B_o$,

$$\overline{T}_{op} = \frac{G_1(\overline{T}_{i1} + \overline{T}_e) + G_2(\overline{T}_{i2} + \overline{T}_e) + \cdots + G_n(\overline{T}_{in} + \overline{T}_e)}{\dfrac{1}{n}(G_1 + G_2 + \cdots + G_n)}. \qquad (21)$$

For the equally simple case in which the gains are equal, at all responses $G_1 = G_2 = \cdots = G_n$, and the S_i's are arbitrary but uncorrelated, we have $G_s = G_1$ and

$$\overline{T}_{op} = (\overline{T}_{i1} + \overline{T}_e) + (\overline{T}_{i2} + \overline{T}_e) + \cdots + (\overline{T}_{in} + \overline{T}_e). \qquad (22)$$

$\overline{T}_e$, of course, is obtained as before from (12).

From the above discussion it can be seen that when the received input signal is distributed over several responses *incoherently*, G_s is never larger than it would be if the received signal were entirely in the response exhibiting the largest gain. Hence, for the case in which all response gains are equal, G_s and thereby $\overline{T}_{op}$ [(22)] are independent of how the uncorrelated input signal is distributed over the various responses. With $\overline{T}_{op}$ (and B_o) constant, the output signal-to-noise power ratio

$$\frac{S_o}{N_o} = \frac{S_i}{k\overline{T}_{op}B_o} \qquad (23)$$

is seen to depend only on the *total input signal power*.

In receiving man-made signals, this total input signal power is fixed by the transmitter's capability. If we choose to spread it incoherently over several frequency bands—corresponding to the several responses of our receiving system—the power input to each response simply drops and nothing is gained.

However, if no limitation of transmitter power exists (as, for instance, in the broad-band radiometry case) the total input signal to our receiving system is proportional to the number of its input responses. This results in a corresponding improvement of S_o/N_o over some other receiving system having the same $\overline{T}_{op}$ but only one input response. For instance, assuming equal gain and equal signal densities in all input responses, S_o/N_o of an n input response receiving system is equal to that obtained with a single response system having an operating noise temperature equal to $1/n$ times that of the n response system.

Let us now briefly consider the case in which the portions of the input signal that are received by the various responses are partially or totally *correlated*. For this case, the gain G_s will be a more complex function of the various response gains $G_1, G_2, \cdots, G_n$, and depend also on the degree of correlation as well as the combining process at the output of the receiving system. However, with all contributing factors specified, one can always determine G_s and $\overline{T}_{op}$ from their basic definitions.

D. Relation Between Various Noise Temperatures and Noise Factor

In this paper, the concepts $\overline{T}_{op}$, T_{op}, $\overline{T}_e$, and T_e have been discussed. These terms have simple relationships to F and $\overline{F}$, the noise figure (factor) and average noise figure (factor).[3] In this section these relationships will be discussed.

For the case of a *single response receiver*,

$$\overline{T}_e = (\overline{F} - 1)290,$$
$$T_e = (F - 1)290. \quad (24)$$

The expression for $\overline{F}$ for measurement purposes can be found from (12) and (24):

$$\overline{F} = \frac{\left[\frac{T_i(\text{hot})}{290} - 1\right] - Y\left[\frac{T_i(\text{cold})}{290} - 1\right]}{Y - 1}. \quad (25)$$

If the "cold" temperature is a 290°K load, we may write (25) as

$$\overline{F} = \frac{\left[\frac{T_i(\text{hot})}{290} - 1\right]}{Y - 1}. \quad (26)$$

For single response receivers, then, concepts of average effective input noise temperature, $\overline{T}_e$, and average noise factor, $\overline{F}$, are equally acceptable provided the IRE definitions are adhered to. For low noise receivers $\overline{T}_e$ is probably the more convenient.

If the contribution of the load-noise can be neglected, the operating noise temperature and the average operating noise temperature for the single response receiver can be written as

$$T_{op} = T_i + T_e$$
$$\overline{T}_{op} = \overline{T}_i + \overline{T}_e \quad (27)$$

so that

$$T_{op} = T_i + (F - 1)290$$
$$\overline{T}_{op} = \overline{T}_i + (\overline{F} - 1)290. \quad (28)$$

For a multiple response receiver, the noise factor can be simply and directly related to operating noise temperature only for the special case when the generator is 290°K and the signal is in one response only. For this case

$$T_{op} = 290F.$$

E. Conclusion

The foregoing indicates that one very important characteristic of a receiving system is the signal-to-noise ratio, S_o/N_o, at the output of the system. The system designer can evaluate S_o/N_o from the knowledge of the average operating noise temperature $\overline{T}_{op}$, the output signal bandwidth B_o, the total input signal power S_i, and the signal gain G_s.

The component designer must supply data of sufficient generality so that the values of these quantities can be computed. For this purpose he must supply information on the average effective input noise temperature, $\overline{T}_e$, which he can measure by (12). He must specify the gains of the various responses and their signal and noise bandwidths. The system designer can use these values to calculate his particular system's average operating noise temperature, $\overline{T}_{op}$, by inserting them together with his signal output bandwidth, B_o, and his particular input termination noise temperatures, T_i's, into the general equations (13) and (14), or any appropriate simpler form. (For instance: (16) for the single response receiver; (18) for the multiple input response receiver with signal in only one response; (22) for multiple input responses with equal gains and uncorrelated input signals which are arbitrarily distributed, etc.) From this value of $\overline{T}_{op}$, the output SNR may be calculated from (23).

Appendix[10]

IRE Definition of Noise Figure
(Taken from 57 IRE 7.S2, July Proc. IRE)

Noise Factor (Noise Figure) (of a Two-Port Transducer). At a specified input frequency the ratio of 1) the total noise power per unit bandwidth at a corresponding output frequency available at the output *Port* when the Noise Temperature of its input termination is standard (290° K) at all frequencies (Reference: Definition for Average Noise Factor) to 2) that portion of 1) engendered at the input frequency by the input termination at the *Standard Noise Temperature* 290° K).

Note 1: For heterodyne systems there will be, in principle, more than one output frequency corresponding to a single input frequency, and vice versa; for each pair of corresponding frequencies a *Noise Factor* is defined. 2) includes only that noise from the input termination which appears in the output via the principal-frequency transformation of the system, *i.e.*, via the signal-frequency transformation(s), and does not include spurious contributions such as those from an unused image-frequency or an unused idler-frequency transformation.

Note 2: The phrase "available at the output *Port*" may be replaced by "delivered by system into an output termination."

Note 3: To characterize a system by a *Noise Factor* is meaningful only when the admittance (or impedance) of the input termination is specified.

Noise Factor (Noise Figure), Average (of a Two-Port Transducer). The ratio of 1) the total noise power delivered by the transducer into its output termination when the *Noise Temperature* of its input termination is standard (290° K) at all frequencies, to 2) that portion of 1) engendered by the input termination.

[10] For clarity, the underlined words have been added to the IRE Standard Definitions.

Note 1: For heterodyne systems, 2) includes only that noise from the input termination which appears in the output via the principal-frequency transformation of the system, *i.e.*, via the signal-frequency transformation(s), and does not include spurious contributions such as those from an unused image-frequency or an unused idler-frequency transformation.

Note 2: A quantitative relation between the *Average Noise Factor* $\overline{F}$ and the *Spot Noise Factor* $F(f)$ is

$$\overline{F} = \frac{\int_0^\infty F(f)G(f)df}{\int_0^\infty G(f)df}$$

where f is the input frequency, and $G(f)$ is the transducer gain, *i.e.*, the ratio of 1) the signal power delivered by the transducer into its output termination, to 2) the corresponding signal power available from the input termination at the input frequency. For heterodyne systems, 1) comprises only power appearing in the output via the principal-frequency transformation *i.e.*, via the signal-frequency transformation(s) of the system; for example, power via unused image-frequency or unused idler-frequency transformation is excluded.

Note 3: To characterize a system by an *Average Noise Factor* is meaningful only when the admittance (or impedance) of the input termination is specified.

Noise Factor (Noise Figure), Spot. See:

Noise Factor (Noise Figure) (of a Two-Port Transducer).

Note: This term is used where it is desired to emphasize that the *Noise Factor* is a point function of input frequency.

Noise Temperature (at a Port). The temperature of a passive system having an available noise power per unit bandwidth equal to that of the actual *Port*, at a specified frequency.

Note: See *Thermal Noise.*

Noise Temperature, Standard. The standard reference temperature T_o for noise measurements is 290° K.

Note: $kT_o/e = 0.0250$ volt, where e is the magnitude of the electronic charge and k is Boltzmann's constant.

The In-Line Cryotron*

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Summary—This paper describes a new type of planar thin-film cryotron namely, an in-line cryotron, and compares its advantages to the crossed-film cryotron. This cryotron has its gate and control elements superimposed and parallel, or in-line, whereas the crossed-film device has its gate and control elements crossed at right angles.

The gain curve for the in-line cryotron has a region where incremental gains of one to ten may be obtained without a change in the gate-to-control width ratio Wg/Wc whereas large gains are not possible for the crossed-film cryotron without altering the width ratio. Larger gate resistances are possible within the in-line cryotron and calculations are given to show it is feasible to properly terminate low impedance strip transmission lines with characteristic impedances in the range of 0.1 to 1.0 ohms. It is necessary to properly terminate the strip transmission lines commonly used in superconducting circuit fabrication in order to achieve the maximum circuit switching speeds.

Other advantages and the disadvantages of the in-line crytron are also discussed.

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Introduction

The purpose of this paper is to describe a new type of evaporated, thin-film superconductive switching component called the "in-line cryotron." It differs in structure from the crossed-film planar cryotron previously discussed in the literature, primarily in the sense that its soft superconductive gate film and hard superconductive control film are parallel, superimposed, and of equal width rather than at right angles to one another.