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This study was concerned with improving the performance of electrically small antennas through the use of active-network techniques. Only antennas for the range 30-80 MHz were considered, and means were sought for reducing the noise figure of a receiving system employing such an antenna. Two types of active coupling networks were studied: negative-immittance converters (NIC), and feedback amplifiers. The results obtained show that an FET with feedback appears useful, whereas a NIC is impractical because of its excessive noise and its high sensitivity to changes in circuit and bias parameters.

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FINAL RESEARCH FINDINGS

I OBJECTIVE

The objective of this research program was to improve the performance of electrically small antennas through the use of active network techniques. For receiving antennas, improvement in performance essentially means obtaining good signal-to-noise ratios over wide bandwidths. For transmitting antennas, one is more concerned with obtaining good efficiency over wide bandwidths. During this program we have sought to determine the impact on these performance criteria of integrating various classes of active networks into some simple antenna structures such as dipoles and monopoles. Such an integrated antenna structure is called an "active" antenna.

II STATEMENT OF THE PROBLEM AND BACKGROUND

An electrically small antenna tends to be weakly coupled to the radiation field, which means that the ratio of the energy stored on the antenna to the energy radiated per cycle is large. In terms of impedance, this characteristic means that the reactive component of the antenna radiation impedance is always much larger than the resistive component. It is difficult to match such an impedance to a desired optimum impedance over a broad range of frequencies. For a receiving antenna, the desired optimum impedance is one that minimizes the noise figure of the receiver; for a transmitting antenna, it is one that permits the radiation of maximum power.

This difficult impedance-matching situation is aggravated if a cable is used to connect the antenna to the receiver or transmitter. The addition of a cable generally results in increased dissipative losses and nonradiative energy storage in the system, and usually decreases the bandwidth. It was recognized as long ago as 1928 that eliminating the connecting cable and incorporating an amplifier directly into a receiving antenna should improve the antenna performance.[1*] This arrangement has been studied extensively in more recent times.[2-5] Most known methods of obtaining electronic amplification have been tried in this connection, including the use of tunnel diodes[6,7] and parametric amplifiers.[8]

Various degrees of performance improvement have been obtained with these schemes. The use of an FET (common-source) in conjunction with a short monopole has been found to be very effective for the HF frequency range.[9] There are at least two reasons for this: (1) the high external

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[*] References are listed at the end of the report.

noise level at these frequencies mitigates the impedance-matching requirements for minimizing the system noise figure, and (2) an FET provides the desired impedance level without requiring the addition of extra circuit elements.

If one moves to higher operating frequencies, the external noise becomes smaller and thus the achievement of minimum system noise figure requires that the antenna impedance more nearly match the "noise-match" impedance of the first amplifier in the receiver.[5] In the present study, the VHF communication band (30-80 MHz) was of primary interest. Because this frequency range is a transition region between the conditions of high and low external noise, active-antenna design criteria for these frequencies are not well defined. Thus, one aspect of our work has been to study the impact on design of the transitory nature of the external noise.

Most previous work on active-antenna design has assumed, for good practical reasons, that the active network (amplifier) is absolutely stable. However, in order to maintain maximum flexibility in our design study, we did not make this assumption; instead, we permitted the active network to be conditionally stable. In this way, we hoped to learn whether the use of such a circuit in an active receiving antenna could be advantageous.

This study has been limited to the consideration of linear receiving antennas where the signal levels are small and where the current distributions on the radiating elements are not altered by the integration of an active network into the antenna. Thus, we have not considered active transmitting antennas, since there the active network must efficiently handle high power which, in turn, means that the network must be nonlinear. Moreover, in order to improve the basic efficiency of the antenna, the active network must alter the current distributions on the radiating elements. Such schemes are not easily imagined, and so, because of the limited resources of this program, we did not attempt to study this more complex problem.

III RESULTS

A. Introduction

Two different types of active circuits for use in active receiving antennas were studied during this program. These circuits were (1) a negative-immittance converter (NIC), and (2) an amplifier with feedback. In both cases the active circuit was viewed as a linear active coupling network that connected the antenna (a short dipole) to a low-noise preamplifier having a 50-ohm input impedance.

B. Negative-Immittance Converter

In the first part of the program, a receiving system was analyzed by assuming that the output impedance and noise temperature of the active coupling network are independent. Under this assumption we found that the preamplifier's contribution to the system noise figure could be kept to less than twice its minimum possible contribution if the active coupling network were designed to provide a specific output impedance. Some of the possible frequency loci for this desired output impedance lay in the left half of the impedance plane. A network whose output impedance follows any such locus is potentially unstable. However, by including this possibility, we provided an additional degree of design flexibility.

One type of circuit that can generate an impedance with a negative real part is a current-inverting NIC.[10] We designed and built such a circuit, and were successful in achieving the desired output impedance for the active coupling network.

The effect of this NIC coupling network on system noise figure was determined by measuring the ratio of the noise figure of the receiving system as a function of frequency without and with the network connected. The measured results are in qualitative agreement with theory, but the improvement in system noise figure produced by the active coupling network was much less than expected.

We concluded from this result that the NIC was contributing a high level of noise. The reason for this is that the output impedance and input noise temperature of the NIC coupling network are indeed related, and for purposes of controlling system noise figure it is not sufficient to control only the output impedance. The noise-match conditions at the input of the coupling network must also be satisfied. Since the antenna radiation impedance is basically given, the simultaneous achievement of the proper input noise-match conditions and output impedance can be realized only by proper design of the coupling network. The design of such a network can no longer be based on relatively simple equations, and computer-optimization techniques become necessary.

Although it was possible to avoid self-oscillations in the potentially unstable NIC circuit, we noticed that a small change in the bias or other circuit parameters rendered the circuit unstable. This high degree of sensitivity to changes in circuit parameters is an unfortunate characteristic of all NIC circuits,[11] which seriously detracts from their practicality.

C. FET Amplifier with Feedback

In order to minimize the noise figure of a VHF receiving system, we have concluded that it is necessary to control both the gain and output impedance of the active coupling network, as well as its input noise temperature. In the case where the coupling network is a simple amplifier (e.g., a common-source FET), available device parameters generally do not permit the simultaneous achievement of all the desired input and output characteristics. However, an additional degree of freedom is gained when lossless feedback elements are included in the active coupling network. Then, optimum gain and noise-match conditions at the amplifier input can be approximated essentially independently by appropriate adjustment of the feedback elements. This approach cannot reduce the minimum system noise figure that would exist under ideal conditions, but it can improve the actual system noise figure by improving the gain and noise match at the input of the amplifier.

We have studied the effect of both series and parallel lossless feedback in such a receiver system by using computer-optimization design techniques. The general results obtained from this study are as follows:

(1) The effect of reactive series or shunt feedback on the noise parameters, particularly the noise-match impedance at the input of the amplifier, is quite similar to the effect that is obtained when the same reactance is connected in series or in shunt at the amplifier input.

(2) Feedback has a strong effect on the S-parameters of the amplifier, particularly S_{11}.

(3) Negative feedback is moderately effective, and positive feedback is quite effective, in causing the input impedance of the amplifier to differ significantly from its noise-match impedance. Such behavior is necessary if simultaneous gain and noise matching are to be achieved.

In order to illustrate what the use of feedback might achieve in the VHF communication band, we considered a specific example. We selected a 2N5398 FET for the active coupling network. Its S parameters are listed as functions of frequency in Table 1. The noise parameters of this transistor were assumed to be constant over the frequency range of interest. The assumed values of these parameters were:

- Minimum noise temperature = 290°K
- Noise-match impedance = 500 + j0 ohms.

The antenna in this example was assumed to be a short dipole whose half-length was 1/16 wavelength at 30 MHz. The parameters for this antenna are listed as functions of frequency in Table 2. Here $Z_A = R_A + jX_A$ is the antenna impedance and T_A is the external noise temperature ($T_0 = 290^{\circ}$K). Finally, we assumed that the input and noise-match impedance of the preamplifier were both equal to 50 ohms, that its correlation resistance was zero, and that its noise temperature was 93°K.

A schematic diagram of the optimized active coupling network determined for this example is shown in Figure 1. No bias networks were

Table 1

S PARAMETERS FOR A 2N5398 FET

Frequency (MHz)	S_{11}	S_{12}	S_{21}	S_{22}
30	0.994-j0.083	0.0014+j0.0199	-0.791-j0.103	0.993-j0.05
35	0.992-j0.095	0.0017+j0.0225	-0.789+j0.117	0.993-j0.055
40	0.990-j0.108	0.0021+j0.025	-0.787+j0.131	0.997-j0.06
45	0.988-j0.122	0.0026+j0.0278	-0.784+j0.144	0.991-j0.064
50	0.985-j0.136	0.0032+j0.0306	-0.782+j0.158	0.990-j0.068
55	0.983-j0.147	0.0037+j0.0325	-0.779+j0.170	0.989-j0.071
60	0.980-j0.159	0.0042+j0.0344	-0.776+j0.183	0.988-j0.074
65	0.977-j0.171	0.0048+j0.0367	-0.771+j0.195	0.987-j0.077
70	0.974-j0.184	0.0055+j0.0390	-0.765+j0.207	0.986-j0.080
75	0.971-j0.196	0.0062+j0.0414	-0.760+j0.217	0.985-j0.083
80	0.968-j0.208	0.0069+j0.0438	-0.754+j0.231	0.984-j0.087

Table 2

ANTENNA PARAMETERS

Frequency (MHz)	R_A (ohms)	X_A (ohms)	T_A/T_0
30	1.54	-680	33.3
35	2.10	-583	24.5
40	2.74	-510	18.8
45	3.47	-453	14.8
50	4.28	-408	12.0
55	5.18	-371	9.9
60	6.17	-340	8.3
65	7.40	-311	6.9
70	8.80	-285	5.7
75	10.30	-261	4.4
80	11.90	-240	3.1

explicitly included in the circuit, but in the frequency range of interest, near-ideal characteristics can be expected for most bias circuits. The circuit was optimized with the objective of minimizing both the operating noise figure of the system and the ripples in the transducer gain. The computed results for these quantities are plotted as a function of frequency in Figure 2.

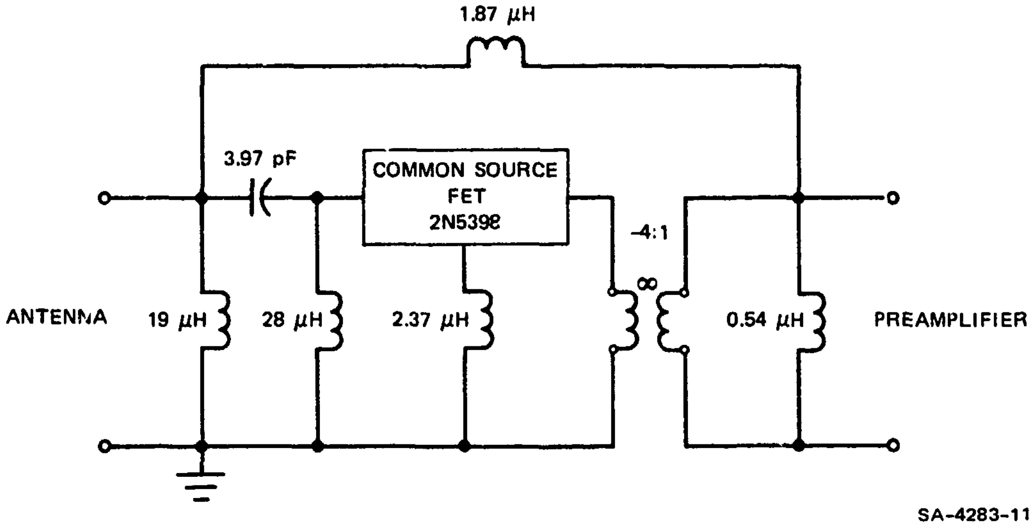

FIGURE 1 SCHEMATIC DIAGRAM OF OPTIMIZED ACTIVE COUPLING NETWORK

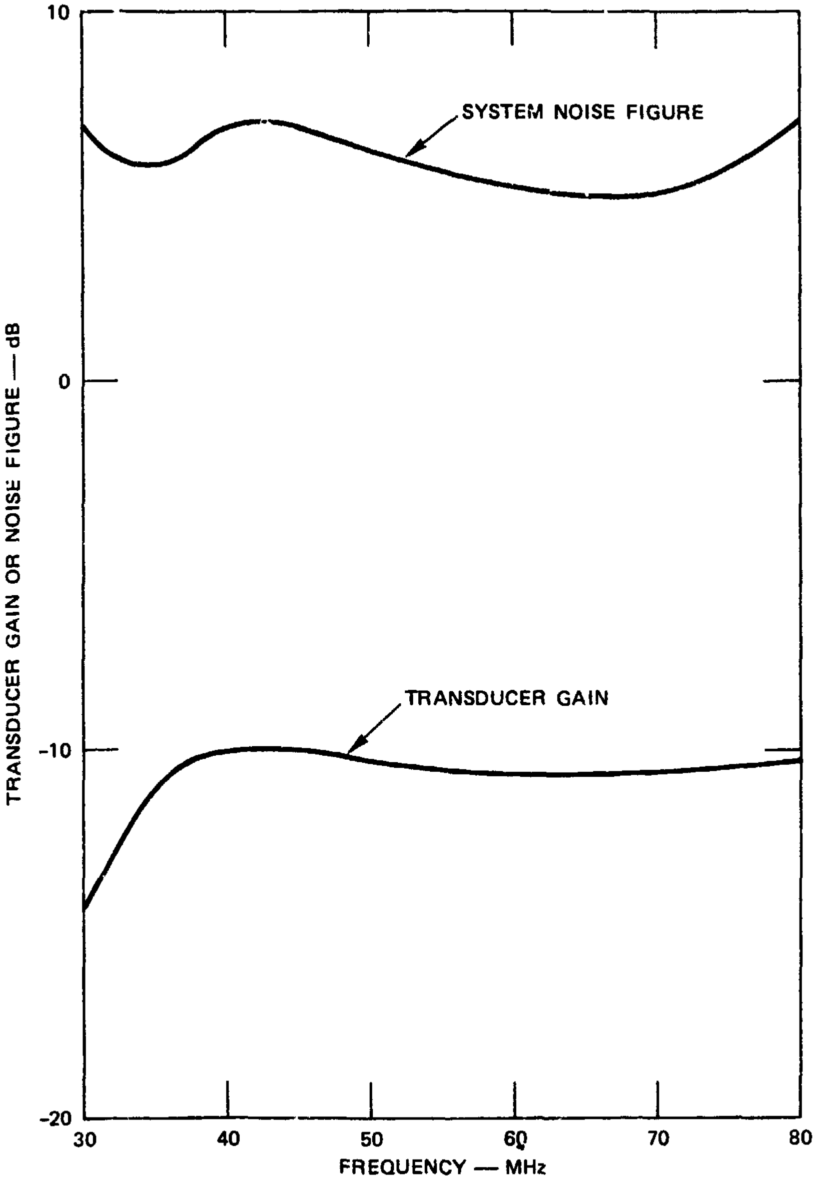

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FIGURE 2 NOISE FIGURE AND GAIN AS FUNCTIONS OF FREQUENCY FOR OPTIMUM ACTIVE COUPLING NETWORK

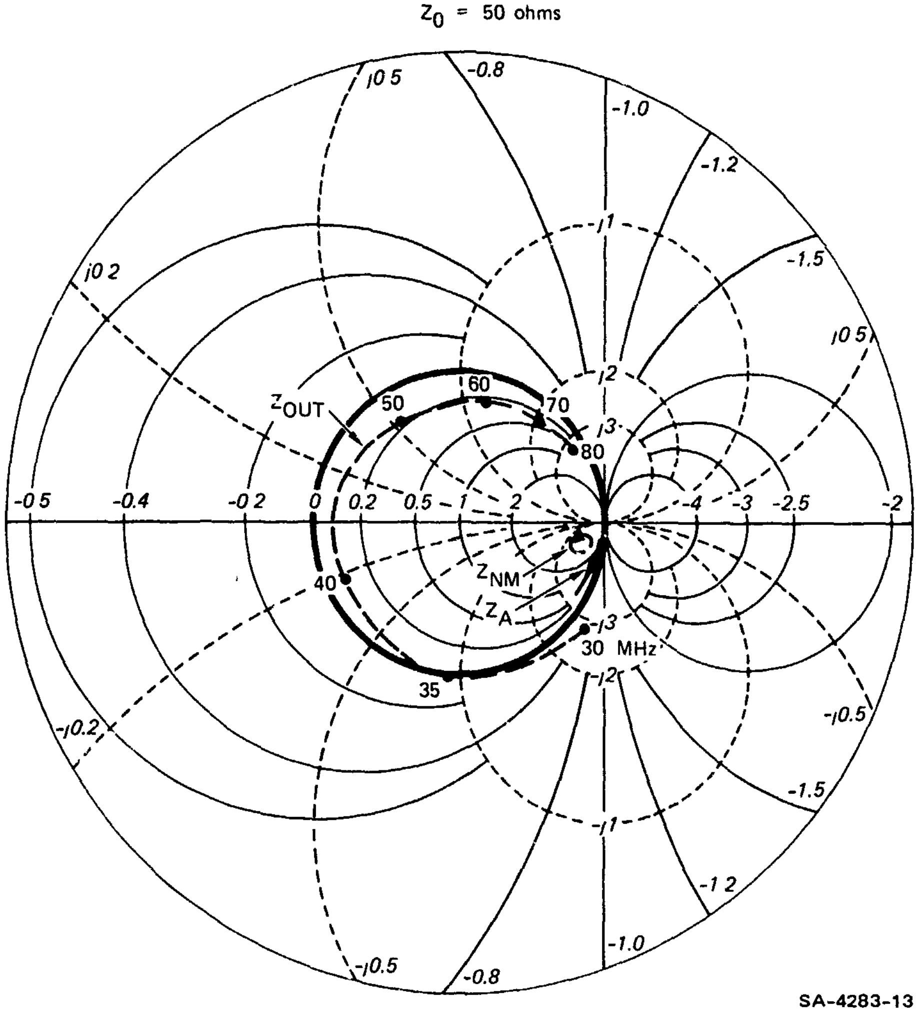

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FIGURE 3 OUTPUT AND NOISE-MATCH IMPEDANCES AS FUNCTIONS OF FREQUENCY FOR OPTIMUM ACTIVE COUPLING NETWORK

The computed output impedance (Z_{OUT}) of the optimized active coupling network is shown plotted as a function of frequency in the Smith chart of Figure 3. We see that the circuit is potentially unstable in the lower part of the frequency range of interest. However, the system is stable in this frequency range, since the input impedance of the preamplifier that follows the coupling network is 50 ohms. It appears, though, that the system might be unstable at frequencies below 30 MHz. This possibility emphasizes the need for using design data that cover a much broader range of frequencies than just the band of interest.

Also shown in Figure 3 is the locus for the noise-match impedance (Z_{NM}) of the active coupling network. In order to minimize the noise contribution of the coupling network, the noise-match impedance should be equal to the antenna impedance (Z_A). However, it is not possible to satisfy this condition over a finite range of frequencies. Instead, we used computer optimization to determine the best approximation to this condition. In this case, the optimization caused the noise-match impedance to generate a loop in the reflection-coefficient plane (Smith chart). This behavior was achieved by using a coupling network that incorporated both series feedback (negative) and parallel feedback (positive).

Finally, in Figure 4 we compare the results obtained for the optimized active coupling network with those obtained for three other coupling schemes. These three schemes are: a three-element passive (and lossless) matching network that attempts to match the antenna impedance to the noise-match impedance of the common-source FET amplifier (Curve 2); a transistor with no matching network (Curve 3); and a direct connection between the antenna and the preamplifier (Curve 4). We see that the active coupling network with feedback produces an improvement in noise figure of between 1 and 8 dB over the directly connected system. Use of a transistor alone is actually worse than a direct connection for frequencies in the upper half of the band. This situation occurs because the decrease in external noise at high frequencies makes the achievement of a noise match between the transistor amplifier and the antenna more critical.

It is interesting to see in Figure 4 that an optimized passive coupling network performs about as well as an active coupling network, except that the noise figure in the passive case exhibits much more variation as a function of frequency. Such fluctuations could be detrimental in some applications. In addition, the actual performance of a passive coupling network will be degraded by the presence of dissipation losses in the network elements. Thus, in practice, it appears that the performance of an active coupling network will probably be superior in the VHF communication band under consideration.

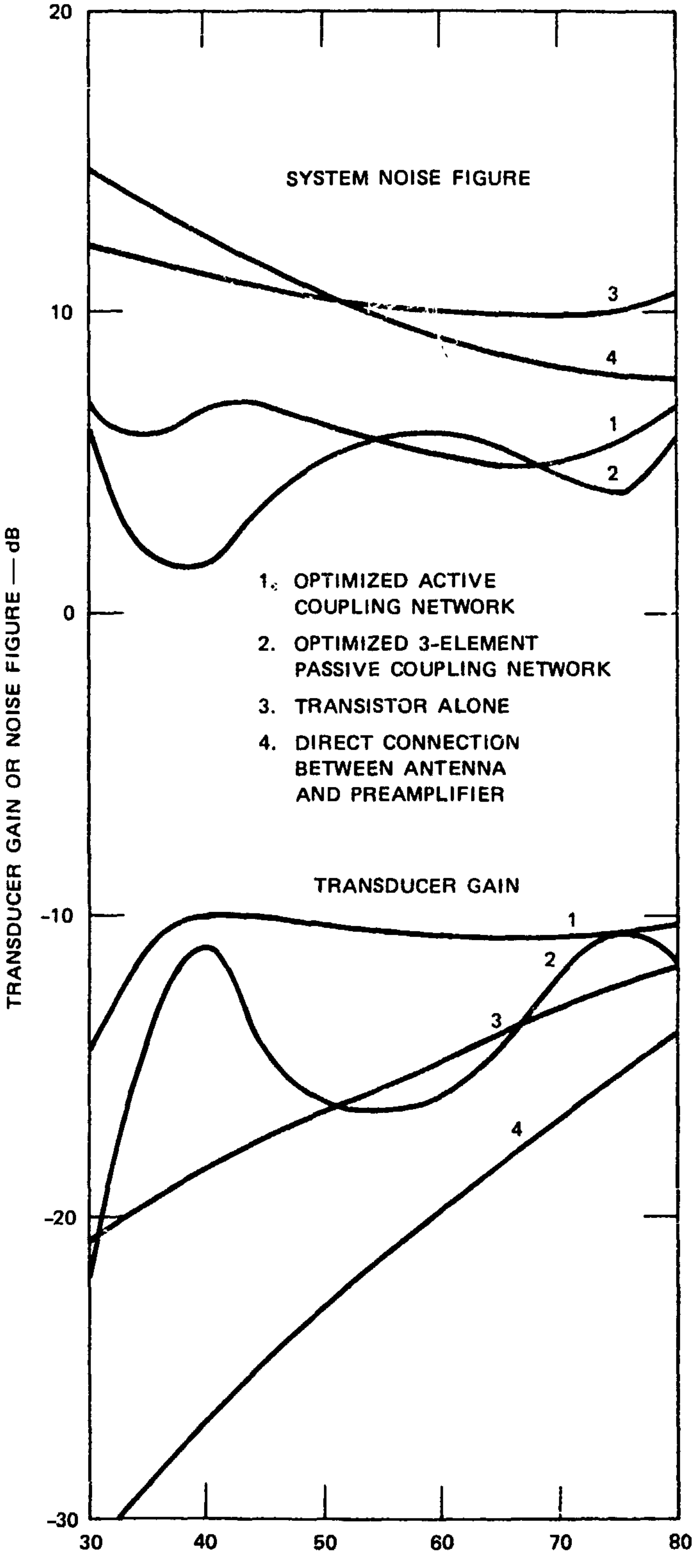

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FIGURE 4 COMPARISON BETWEEN DIFFERENT COUPLING NETWORKS

The characteristics of the receiving system considered in this example have also been calculated for frequencies below 30 MHz. We found that, in agreement with Lindenmeier,[9] because of the high level of external noise, a significant improvement in system performance can be achieved by connecting an FET directly to the short dipole without any feedback or other embedding networks. Since the radiation Q of an antenna of a given size increases with decreasing frequency, the performance of passive coupling networks generally becomes poorer as frequency decreases, thus making the use of an FET coupling network even more attractive for the HF range.

IV CONCLUSIONS

In general, an active coupling network that interconnects an electrically small receiving antenna and an amplifier can improve the overall system noise figure if the noise properties of the coupling network are equal to, or better than, those of the amplifier. Because of their high input impedance, FETs seem to be well suited for coupling to electrically small dipoles. In the HF range, the use of an FET by itself results in improved system performance. At higher frequencies, the incorporation of feedback into the FET circuit is beneficial.

In some cases where wide bandwidths are required, it appears advantageous to permit the active coupling network to be potentially unstable. However, in this situation, out-of-band oscillations are often difficult to suppress. In particular, the NIC circuit studied during this program proved to be difficult to stabilize, as well as being excessively noisy.

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