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The Noise Performance of an Active, Linear Antenna Array for Reception

William R. Panton, James B. Beyer

University of Wisconsin, Madison

ABSTRACT

The noise performance of an active receiving antenna array with endfire pattern was studied using "Noise Wave Analysis". Gallium Arsenide, Field Effect Transistors (GaAs FET's) were used. The array signal combining was accomplished with a series feed identical to the output transmission line of a Distributed Amplifier. A single stub tuner was simulated between each antenna element and active device (FET's in this case). System noise performance was simulated as the transformation due to the tuners was varied. The configuration giving best noise performance was found. Finally, two, four, six, and eight element active arrays were built and tested at 2 GHz confirming the analysis.

INTRODUCTION

This work addresses two aspects of active, linear, receiving arrays: the feed network, and system noise performance. A series feed network was implemented in a manner identical to the output transmission line of a distributed amplifier. GaAs FET's were used as active devices, but the ideas can be applied to other active devices. The drain terminal of each device was connected to two inductors forming a "T" section with the drain to source capacitance (See Fig. 1). The inductor values were chosen so that the resulting characteristic impedance of the "T" section was 50Ω (see Beyer [1]). This technique is a simple and effective way to implement signal summing without using three port summing networks.

Driving the inquiry into system noise performance was the question of whether an active array could have noise performance on par with that of a similar passive array followed by a receiver. The active array has $n - 1$ more noisy active devices (n is the number of antenna elements) than the passive system. The active array can be designed such that the antenna elements see nearly an open circuit. This allows the open circuit voltage at the element terminals to remain constant as elements are added to the array. In this case the system's power gain increases as n^2 while the noise power at the output increases as n. Such simplification ignores issues including the effect of input matching on device noise performance and mutual coupling between array elements. These interdependent effects can be accounted for conveniently using the "Noise Wave Analysis" technique of simulating noise behavior. [2,3]

"Noise Wave Analysis" was used to study active receiving arrays with the topology of Fig. 1 as the transformation due to the matching network was varied.

Active receiving arrays with two, four, six, and eight elements were built and tested to verify the predictions made by the simulations.

NOISE WAVE ANALYSIS

Noise Wave Analysis was used in the simulation of the active antenna array system [2,3]. The method is a modification of the scattering parameter description used for linear circuits. Each component is described by incident ($\underline{\mathbf{a}}$) and reflected ($\underline{\mathbf{b}}$) waves as well as noise generated within the component ($\underline{\mathbf{c}}$).

$$\underline{\mathbf{b}} = [\mathbf{S}]\ \underline{\mathbf{a}} + \underline{\mathbf{c}} \qquad 1$$

The noise components are described by a correlation matrix.

$$[\mathbf{C}] = \underline{\mathbf{c}}\ \underline{\mathbf{c}}^{\dagger} \qquad 2$$

The transpose, then conjugate of the vector is denoted †. The elements in [C] have units of Watts. The correlation matrix of a passive component can be found from its scattering parameters.

$$[\mathbf{C}] = k\, T_x\, BW\, \left([1] - [\mathbf{S}][\mathbf{S}]^{\dagger}\right) \qquad 3$$

Boltzman's constant is designated k, bandwidth is denoted BW, T_x is the physical temperature. S.W. Wedge [3] gives the correlation matrix in terms of the familiar two-port noise parameters and the scattering parameters of the device. This was used to find the correlation matrix for the FET's.

The techniques outlined in J.A. Dobrowolski [2] were used to simulate the system of interconnected components that comprise the antenna array. The antenna structure was modeled using the moment method program ELNEC. Half wave dipole elements were used. The element to FET matching networks were modeled as noisy attenuators followed by lossless single stub tuners.

The FET's were modeled as shown in Fig. 2. The feed network consists of the "Distributed Amplifier" style lumped element transmission line "T" section connected to ideal transmission line segments to add the proper interelement phase shift (Fig. 3). The capacitor C_S is connected in series with the drain to source capacitance of the device. It serves to reduce the loss per transmission line segment [4].

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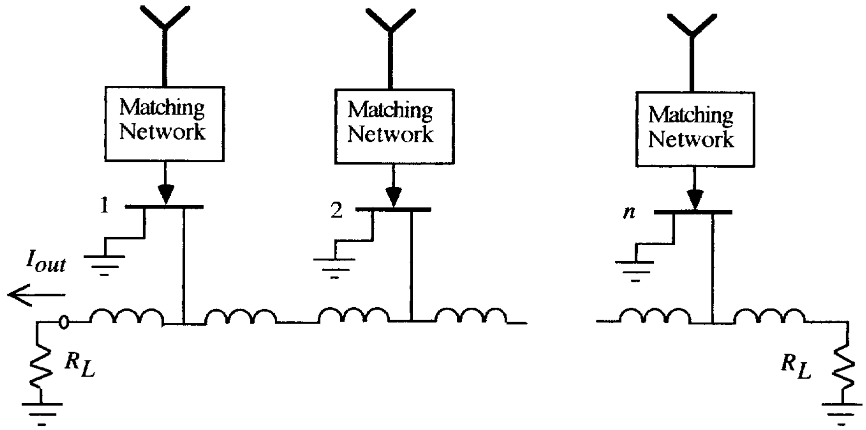

Figure 1. Active Receiving Array.

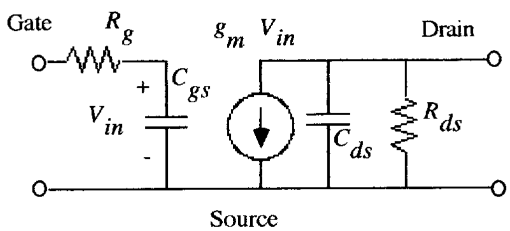

Figure 2. FET Model.

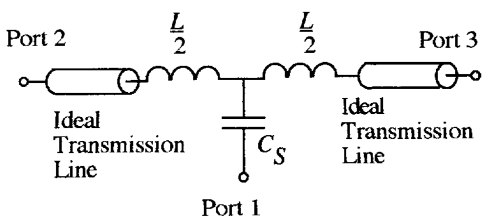

Figure 3. Three Port Interconnect.

SIMULATION RESULTS

The analysis used the NEC71083 FET at 2 GHz for demonstration and for comparison to the experimental results. Results are expressed in effective input temperature. This is a noise temperature referenced to the input of the antenna system. For the case of a lossless, passive antenna followed by a receiver, the effective input noise temperature is the receiver noise temperature divided by the gain of the passive antenna.

$$T_{ineff} = \frac{T_{RCVR}}{G_{Antenna}} \qquad 4$$

This convention is used because the active receiving antenna cannot be easily broken down into a lossless passive antenna with a receiver following it. The antenna and receiver are integrated together. The effective input noise temperature is the reciprocal of the commonly used G/T ratio if the contribution of sky noise to the G/T ratio is set to zero. [5]

Table 1 shows the simulated noise performance results for two, four, six, and eight element endfire arrays for the conditions of: FET to element match, nearly open circuit shown to the antenna elements, and the condition for best noise performance of the system. The nearly open circuit condition was obtained by simply rotating the input admittance of the FET's with transmission line to the point closest to open circuit. Table 2 shows the active antennas' gain corresponding to those conditions.

Number of Elements	FET Matched to Element (°K)	Open Circuit (°K)	Optimum System Noise (°K)
2	48.9	54.9	18.7
4	37.5	24.7	9.6
6	33.9	15.9	5.5
8	33.0	11.8	4.1

Table 1. Effective Input Noise Temperature (°K). Simulation Results.

Number of Elements	FET Matched to Element (dB)	Open Circuit (dB)	Optimum System Noise (dB)
2	20.6	12.7	18.2
4	25.0	18.5	22.3
6	28.3	21.9	25.9
8	29.7	24.0	28.6

Table 2. System Gain (dB). Simulation Results.

The simulation was run for admittances (shown to the antenna elements) spanning the Smith Chart. Those listed in the tables were chosen as points of interest. In most cases there are two stub length and shunt susceptance values that show the same admittance to the antenna elements. These two tuner configurations give the same system gain, but *do not* give the same noise performance. The values in the tables correspond to the better of the two configurations. It can be seen that the open circuit condition gives better noise performance (except in the two element case) than the matched condition and that the optimum condition gives significant improvement over those.

The best noise performance does not happen at the position giving best system gain, nor the position giving best FET noise performance. This is due to the intertwined effects of changing FET noise performance and gain with input matching, antenna element loading, and coupling between antenna elements. It was found that noise broadcast back onto the antenna structure, then ending up in the output load had a significant contribution. These factors combine to cause such non-intuitive results.

DESIGN

Active arrays were built to verify the simulated results. Half-wave dipole elements connected to quarter-wave baluns were used. The NEC71083 FET was placed on a Duroid subcircuit. This microstrip subcircuit is shown in Fig. 4.

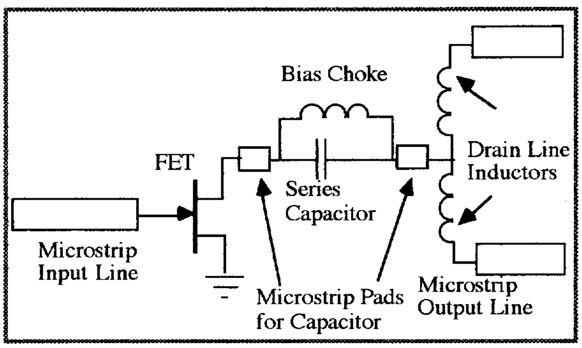

Figure 4. Microstrip Circuit

Loss in the drain transmission line is mostly due to R_{ds}. If the series capacitor were left out and the inductors were chosen to form a 50Ω transmission line, the loss per section would be 0.97 dB. This would create an amplitude taper across the array. A series capacitor value of 0.7 pF was chosen (and the inductor values were recalculated based on the series combination of C_{ds} and C_s [4]) resulting in 0.4 dB loss per section. This level of loss is low enough that the amplitude taper it causes can be offset by ordering the FET's in the array according their gain.

Finally, semirigid coaxial interconnect was cut to bring the phase shift between FET's equal to that caused by the interelement spacing plus one wavelength. The antennas were designed to have no backward lobe by using the element spacing given below.

$$\frac{d}{\lambda} = \frac{1}{2}\left[1 - \frac{3}{4n}\right] \qquad 5$$

This facilitated noise performance testing by reducing the thermal noise received by the antenna when the main lobe was directed toward the sky.

EXPERIMENTAL RESULTS

The radiation patterns of the antennas were measured to verify that the interconnect phase shift was correct. Figure 5 shows the pattern of the eight element active antenna. The antenna was tested in an anechoic chamber. However, the distance between transmitter and test antenna was not quite as long as the far field distance given by the following. [6]

$$R_{ff} > \frac{2D^2}{\lambda} \qquad 6$$

The physical length of the antenna is denoted D. Hence, the measured and calculated patterns differ slightly.

The noise performance of the antennas was measured outdoors to reduce the level of external black body radiation getting into the system. The sky noise was measured so that it could be extracted from the results. Two, four, six, and eight element "open circuit" designs were tested as well as a four element "optimum" design.

Figure 6 gives the measurement results and the corresponding simulated results. Figure 6 also shows the performance of a passive array followed by a receiver that has noise performance equal to the optimum noise performance of one of the devices in the active antenna ($50^{O}K$ found from noise parameter measurements). This passive antenna is assumed to have 0.06 dB resistive loss per element (versus 0.45 dB loss per element in the active antenna's "distributed amplifier"/coax structure). This corresponds to the loss associated with the length of semi-rigid coaxial cable needed to make such a passive array at 2 GHz. Another trace is shown for the case where the passive antenna's loss is increased to 0.5 dB per element. This shows how quickly its performance degrades with increasing loss. This information is key because arrays built with phase shifter circuits will suffer at least this much loss, usually more [7,8,9].

The optimized four element antenna's measured performance ($13.3^{O}K$) was slightly better than the eight element open circuit design's measured performance ($13.6^{O}K$). Hence it is clear that proper element/device mismatch can provide a significant improvement in performance.

CONCLUSIONS

This work shows that the "distributed amplifier" interconnection scheme is a simple and effective alternative to standard three port summing networks. It also shows, with "Noise Wave Analysis" of the system and through experiment, that even though active antennas have $n - 1$ more noisy active devices than a passive array/receiver, they can be designed to have similar or better performance. The active array is particularly suitable for antennas, such as steerable arrays, that have phase shifters or other lossy components between elements.

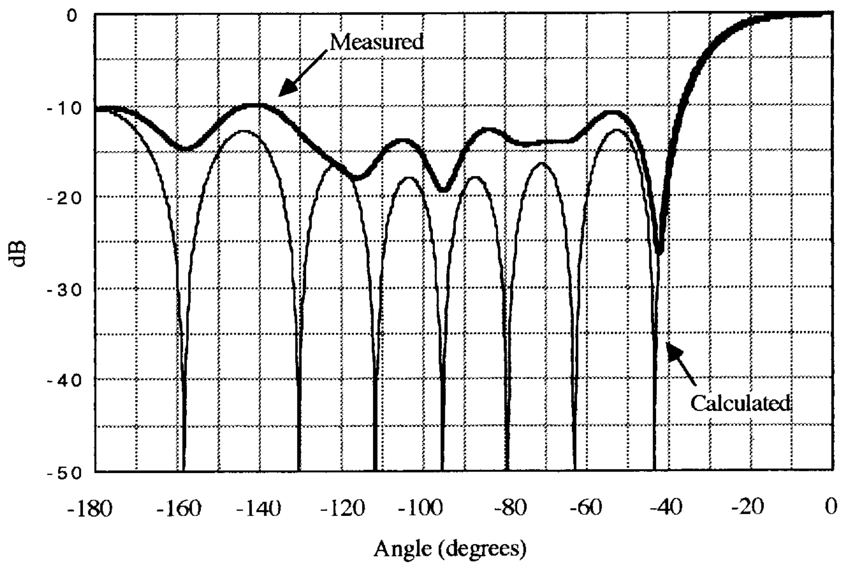

Figure 5. Eight Element Active Receiving Array, Measured and Calculated Radiation Patterns.

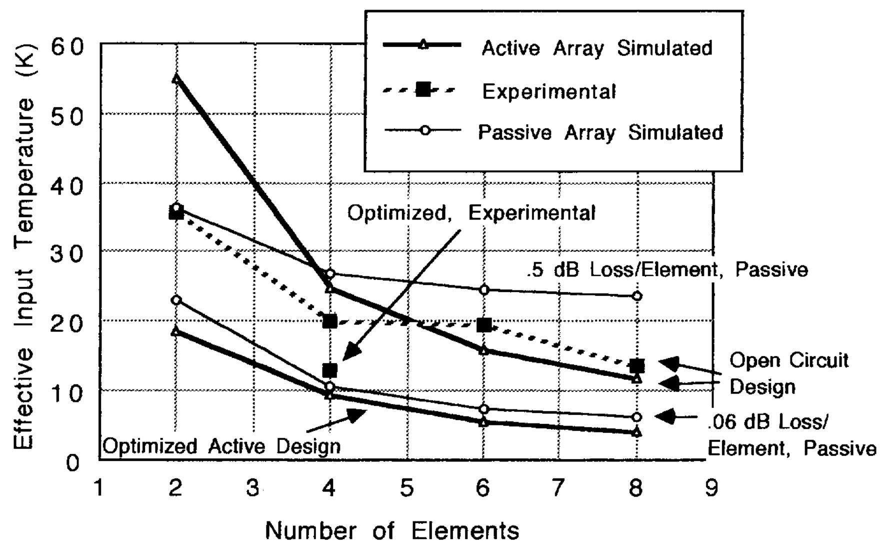

Figure 6. Measured and Simulated Noise Performance vs. Number of Elements.

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