Low Cost Active Antenna Arrays –
Dependence on Array Configuration

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Abstract

Active antenna arrays are very valuable in creating reconfigurable, low-cost, wireless point-to-point networks. These wireless links can be used for a variety of applications from high-speed Internet backbone to multi-media content delivery. The key technical element to a low-cost telecommunication system is to optimize the number of antenna elements and minimize the impact that front end system parameters such as gain, temperature, and noise figure have on the overall circuit. Doing this in an attractive cost-

A formulation for general active array optimization is proposed, integrating front end elements such as low noise amplifier, phase shifter, and arbitrary feed networks. A generalized *G/T* formulation is discussed for active arrays. Tradeoff between module gain/size, feed losses, and amplifier gains/noise figures and their effect on the *G/T* and *SNR* of different arrays is shown.

I. INTRODUCTION

In the design of multi-segmented active array antennas, such as the one shown in Figure 1, a critical system parameter is the *G/T* and noise figure *NF* of the system. *G/T* is the antenna gain over effective system temperature, and is directly related to signal-to-noise ratio at the system output [1]. In the tradeoff study of the array implementation, a good estimate of the system temperature and overall noise figure is necessary. The definition of such parameters also contributes to the ability to compare various array antenna implementations and configurations, as will be presented in the results section of this paper.

In an integrated antenna array, the front end is part of the antenna module; this includes the low noise amplifier (LNA) and power amplifier, and the phase shifter. The front end design and optimization generally includes the LNA and phase shifter distribution over the array structure, integration, and design. The optimal distribution of the gain and phase shifting over the array for maximizing gain, *G/T*, meeting the scan angle requirements, and tolerance constraints have not been thoroughly investigated before. The formulation in this paper should aid in the analysis and optimization of the final active performance of the multi-segment array system.

II. THEORY

For the system trade-off study of an active array a close estimate of the system temperature and the overall noise figure is necessary. With respect to Figure 2, which presents an antenna with N independent channels, such a calculation can be performed for a general active array antenna, where each channel (submodule or subarray) can introduce a different amount of loss to the signal and noise due to different: 1) front end gains of the submodule ($G_{s,j}$), 2) feed losses between the submodule and active amplifier stage ($L_{f,j}$), 3) amplifier parameters (g_j, F_j), 4) down-converter losses, such as phase shifter and combining feed loss ($L_{d,j}$). Previous formulation has been done [1] in the case where the summing network has different weighting factors.

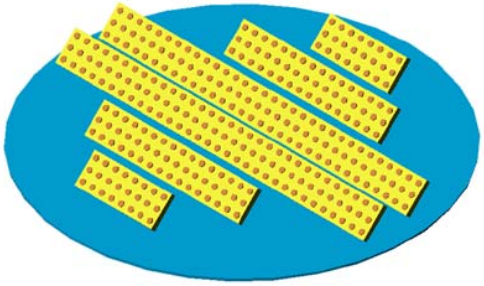

Fig. 1. Multi-module antenna system

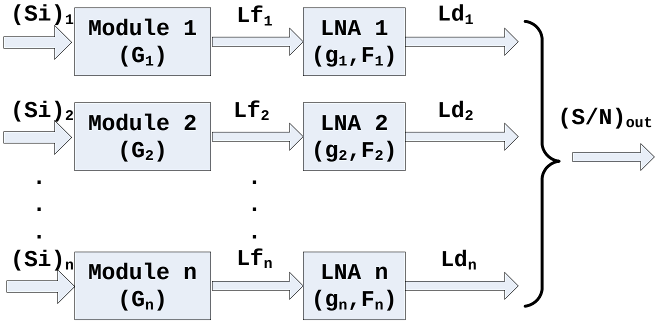

Fig. 2. Multi-module antenna array with integrated independent LNAs

A. General Formulation of Multi-Module Antenna

Due to *G/T* being a measure of signal-to-noise ratio at the output, first the total power of the signal at the sum port of the combining network must be computed. An equivalent noise temperature can be considered using $n_o = kTB$, where k is the Boltzman constant ($k = 1.3806\text{x}10^{-23}$ J/K), and B is the noise bandwidth of the device. We can write the noise output as:

$$N_0 = \sum_{j=1}^{j=N} n_j \tag{1}$$

where n_j is the noise introduced the j^{th} channel, and it is given by:

$$n_j = \frac{kT_{i,j}Bg_j}{L_{f,j}L_{d,j}} + \frac{kT_0B(L_{f,j}-1)g_j}{L_{f,j}L_{d,j}} + \frac{kT_0B(F_j-1)g_j}{L_{d,j}} + \frac{kT_0B(L_{d,j}-1)}{L_{d,j}} \tag{2}$$

where the second term is due to the feed loss right after the antenna ($L_{f,j}$), the third term is the LNA contribution (g_j and F_j), the fourth term is due to the downstream loss ($L_{d,j}$). Note that the first term in Equation 2 contains $T_{i,j}$, which is the sky (input) temperature of each submodule. In the general case the sky temperature of each submodule is different from others in the array due to the module location and orientation. The signal output of the j^{th} channel can be written as:

$$S_{o,j} = \frac{S_{i,j}g_j}{L_{f,j}L_{d,j}} \tag{3}$$

where $S_{i,j}$ is the input signal to the j^{th} element. Then the total signal output can be written as:

$$S_0 = \left(\sum_{j=1}^{j=N}\sqrt{\frac{S_{i,j}g_j}{L_{f,j}L_{d,j}}}\right)^2 \tag{4}$$

where the square root stems from the amplitude combination of the signals.

If we consider a plane wave of power density P incident on the array, each of the previously defined signal powers $S_{i,j}$ can be defined by $S_{i,j} = A_{e,j}P$, where $A_{e,j}$ is the effective area of the j^{th} module. The submodule gain is given by $G_{s,j} = 4\pi A_{e,j} / \lambda^2$, so we can write:

$$S_{i,j} = \frac{G_{s,j}P\lambda^2}{4\pi} \tag{5}$$

and after further manipulation, we can write *G/T* which we are interested in as:

$$\frac{G}{T}=\frac{\left(\sum_{j=1}^{j=N}\sqrt{\frac{G_{s,j}g_j}{L_{f,j}L_{d,j}}}\right)^2}{\sum_{j=1}^{j=N}\frac{T_jg_j}{L_{f,j}L_{d,j}}+\frac{T_0(L_{f,j}-1)g_j}{L_{f,j}L_{d,j}}+\frac{T_0(F_j-1)g_j}{L_{d,j}}+\frac{T_0(L_{d,j}-1)}{L_{d,j}}} \tag{6}$$

Equation 6 takes into account different path losses and amplifier gains. In practice, and for the validation of this model, we consider the case where we use identical LNAs ($F_i = F_j = F$, $g_i = g_j = g$, for $i \neq j$), and if we consider identical path losses ($L_{d,i} = L_{d,j} = L_d$, $L_{f,i} = L_{f,j} = L_f$, for $i \neq j$), Equation 6 can be simplified to:

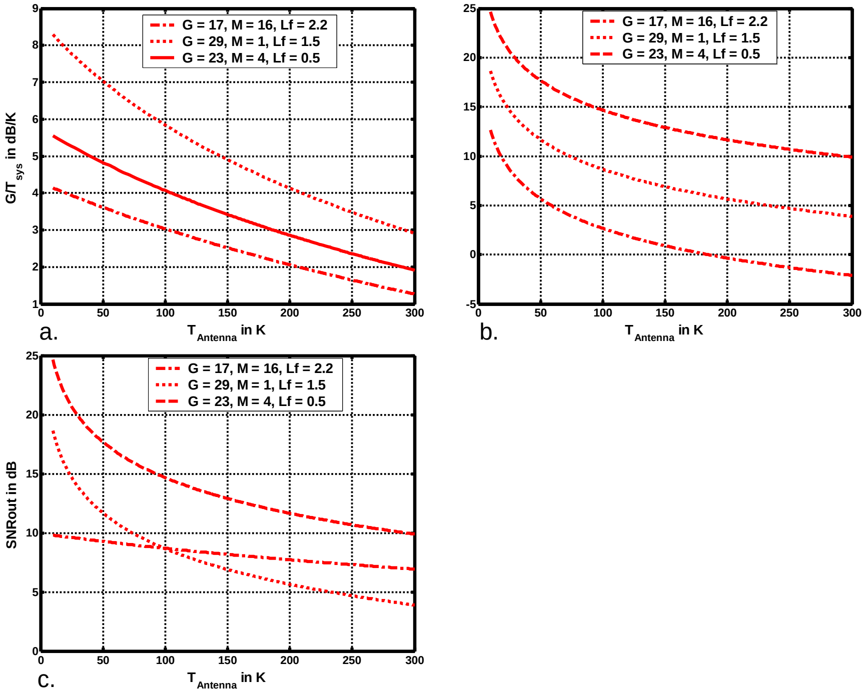

Fig. 3. a) *G/T*, b) SNR_{in}, and c) SNR_{out} for various array configurations

$$\frac{G}{T}=\frac{\left(\sum_{j=1}^{j=N}\sqrt{G_{s,j}}\right)^2}{T_i+T_0\left(L_fF-1+(L_d-1)L_f/g\right)} \tag{7}$$

where T_i is the input temperature considered to be the same for all submodules.

B. Simplification of Developed Theory

In general, it is very difficult to optimize arbitrary arrays using Equations 6, or 7. If all parameters are well known, then Equation 6 will give a good estimate for the overall *G/T* of the system. However, for the purpose of this paper and the presentation of our results, we show an alternative noise figure formulation for comparing various antenna configurations. We can derive the noise figure of the system from Equation 6, with $T_i = T_0$ and the definition of noise figure as the ratio of actual noise power divided by the output noise power that would exist if the system were noiseless and the source would be at room temperature:

$$NF=\frac{kTB}{kT_0B}=L_fF-\frac{L_f}{g}+\frac{L_f}{g}L_d \tag{8}$$

where L_f and L_d are the front-end and downconverter feed losses, and g, F are the gain and noise figure parameters of the amplifier.

III. THEORETICAL RESULTS

The theoretical results are two-fold for our interest. We first consider three antenna configurations: microstrip with submodule gain ($G_{s,j} = 17\ dB$), and consisting of 16 modules. Feed losses are high due to microstrip implementation ($L_{f,j} = 2.2\ dB$). Second, a single large antenna with very high gain ($G_{s,j} = 29\ dB$) and a hybrid waveguide feed structure which minimize feed losses ($L_{f,j} = 1.5\ dB$). Finally, a third antenna combining submodules with high gain ($G_{s,j} = 23\ dB$) and a very low loss feed ($L_{f,j} = 0.5\ dB$). In each case an identical LNA ($g = 20\ dB$, $F = 1.5\ dB$) is added directly after each submodule to compensate for the high losses present before the output (phase shifter, etc.). Using Equations 7 and 8, we show the performance of each of the configurations plotted against the antenna temperature ($T_{antenna}$) as in Figure 3.

If we consider Figure 3a., we clearly see that the highest G/T is achieved by the antenna with the highest front end gain per element. However, it is quickly realized (Figure 3b. and Figure 3c.) that the highest SNR_{out} ratio is obtained from the antenna with the lowest feed loss. It is therefore more important to achieve a low feed loss than front element gain in order to have successful signal recovery at the output.

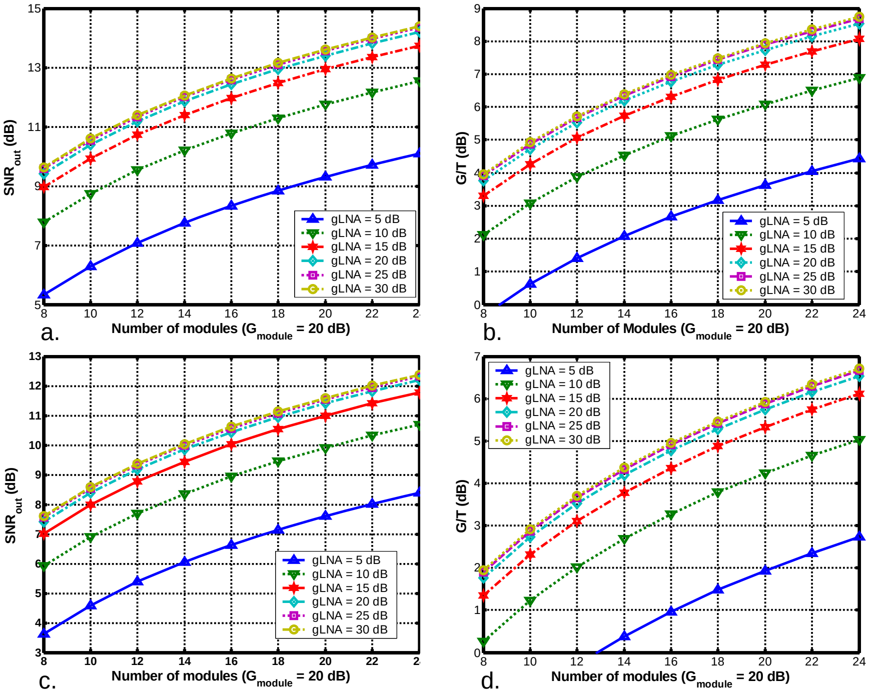

Fig. 4. a) SNR_{out}, b) G/T for $L_f = 0.5\ dB$ (low loss) and
c) SNR_{out}, d) G/T for $L_f = 2\ dB$ (high loss) feed system comparison

Secondly, in Figure 4, we fix the submodule gain ($G_s = 20\ dB$), and investigate the variation of G/T and SNR_{out} with different number of modules in the configuration, and for various LNA gains. $T_{antenna} = 150\ K$ and is maintained fixed for this analysis. Figures 4a., b. present the SNR_{out} and G/T in the case of low feed loss antenna, and Figures 4c., d. present SNR_{out} and G/T for high feed loss. The basis of these curves can be used as optimization for a prescribed G/T ratio or SNR_{out}.

IV. CONCLUSION

We have presented a general formulation for combining N non-identical antenna submodules into an array using an unbalanced feed network. The analysis was done considering G/T and SNR issues, and results for G/T and SNR improvement or degradation depending on particular antenna configurations were shown.

In the discussion of the overall antenna development, the overall goal is to complete the entire array, consisting of the radiating elements, feed, low noise amplifier, as well as phase shifter and to integrate all the elements together. Due to the noise figure of the LNA and additional losses in the system, it is critical to reduce the feed loss as close to the antenna elements as possible.

V. ACKNOWLEDGEMENT

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REFERENCES

[1] J. J. Lee, "G/T and Noise Figure of Active Array Antennas," *IEEE Transactions on Antennas and Propagation*, vol. 41, no. 2, pp. 241-244, February 1993