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Noise figure analysis of beamforming systems

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Abstract

The effect of Low Noise Amplifier (LNA) and power combiner on the overall noise figure of a receiver chain are analyzed and presented for a typical receiver system employing analog and digital beamforming network configuration. The analysis of noise figure is carried out under single and multichannel receiver configurations (2 to 256 antenna elements) for phased array and MIMO antenna systems. Results are presented for noise figure at each subsection of the receiver blocks. Which clearly demonstrate that the noise figure of the receiver chain is predominately controlled by the position of the LNA and power combiner. Subsequently, the overall noise figure is also presented for three typical configurations comprising of: 1. Signals are combined, amplified and down-converted. 2. Signals are amplified, combined and down converted. 3. Signals are first amplified and down converted before combining. For an antenna array with a LNA of 3 dB noise figure irrespective of its size, the 2nd and 3rd configurations give 1 dB overall improvement.

1. Introduction

5G network at mmWave frequency has its own advantages and drawbacks. The mmWave signals cannot pass through obstacles and path loss at mmWave frequencies are higher due to the small aperture area of the antenna element. Beamforming is primarily used to address these problems. In a beamforming system the antenna signals are focused towards the intended direction rather than broadcasting to all directions unnecessarily. This approach increases the signal power and reduces the interference and thereby enhance the receiver sensitivity.

The phased array antenna is used to increase aperture area to receive more signals. In a typical receiving system two or more antennas are spatially arranged and connected to a common receiver to receive the signal from a predefined direction. The beamwidth is proportional to the number of antenna elements, the direction of propagation is controlled by providing the phase difference between antenna elements, and the amplitude weights determine the side lobe level [1].

In this paper, the effect of placement of LNA, power combiner, and mixer on overall system noise figure is analyzed for different types of beamforming system configurations. Section 2 describes different types phased array systems, Section 3 gives the simulated noise figure of each block and the results are presented here and section 4 concludes the paper.

2. Array configurations

2.1 Fixed beam antenna array (Type I)

In a fixed-beam antenna array system, signals from all elements are combined, down-converted and given to the base band system for further processing. Figure 1. a shows the block diagram of fixed beam antenna array. The amplitude and phase weights are fixed here. Hence it creates a radiation pattern with fixed direction and beamwidth.

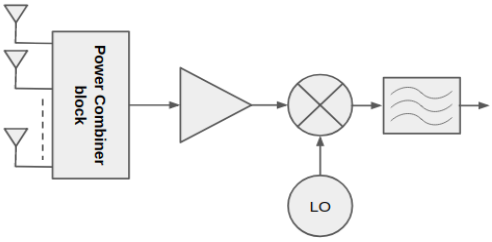
2.2 Analog beamforming (Type II)

Figure 1. b is an analog beamforming antenna system, here the amplitude and phase weights are applied before combining. The combined signal will have the desired pattern. Generally, the weights are calculated from the base band section and applied directly on the RF signals using programmable phase shifters and attenuators. This configuration has only one downconverter block.

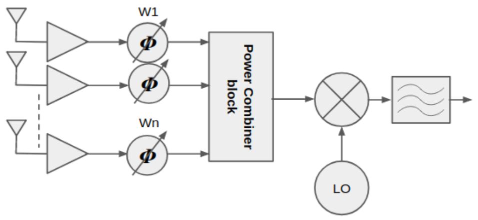
2.3 Digital beamforming (Type III)

In digital beamforming, the signals received by the antenna elements are separately down converted from RF signal frequency to IF signal frequency. Analog to digital (ADC) converters are employed to digitize the signal. Complex weights are then applied to the digitized signals. The resultant base band signal gives the desired directional antenna pattern. This method is complex and costly.

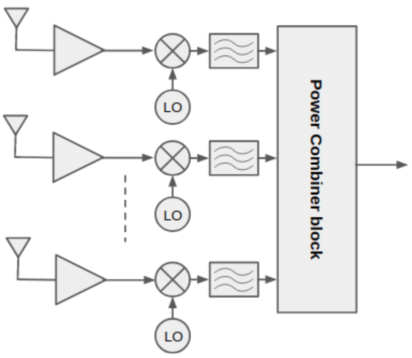
The hardware configurations are decided based on the practical applications. The three configurations are simulated and compared here for their overall noise figure performance.



(a)



(b)



(c)

Figure 1. beamforming configurations (a) Fixed beam array antenna system, (b) Analog beamforming with amplitude and phase control weights, (c) digital beam forming (MIMO system)

3. Noise figure simulation

The noise figure (NF) is defined as the ratio of the total output noise power to the output noise power caused only by the source [2]. For a single antenna receiver case, it is given by

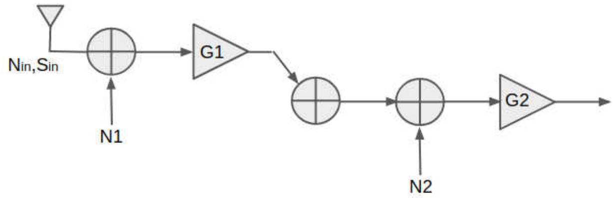
$$NF = 10\log\left(SNR_{input}\right) - 10\log\left(SNR_{output}\right) \quad (1)$$

Noise figure measures the degradation of the signal-to-noise ratio (SNR), caused by components, such as amplifiers, filters in an RF signal chain. The cascaded noise figure is

$$F = F1 + \frac{F2-1}{G1} + \frac{F3-1}{G1G2} + \frac{Fn-1}{G1G2..Gn} \quad (2)$$

In the case of array system, the signals are combined at the power combiner where signals are added coherently and the uncorrelated noise picked up by the antenna elements cancel each other to give an improved signal to noise ratio.

From [3],



$$S_{Out} = n^2 . G_{1.} G_{2.} S_{In} \quad (3)$$

$$N_{Out} = n\left(N_{In} + N_1\right) G_1 G_2 + N_2 G_2 \quad (4)$$

$$F = \frac{n\left(N_{in} + N_1\right) G_1 G_2 + N_2 G_2}{n N_{In} G_1 G_2} \quad (5)$$

$$F = n \frac{SNR_{In}}{SNR_{Out}} \quad (6)$$

Overall gain is given by

$$G_{Total} = G_{SingleElement} + 10\log(n) \quad (7)$$

Where, n is the number of antenna elements

By increasing the number of antenna elements one can get SNR_{out} better than the SNR_{input}. Figure. 2 shows the noise figure plot of the three configurations. Initially, the value is 3 dB for single antenna case and drastically reduces as the number of antenna elements increases.

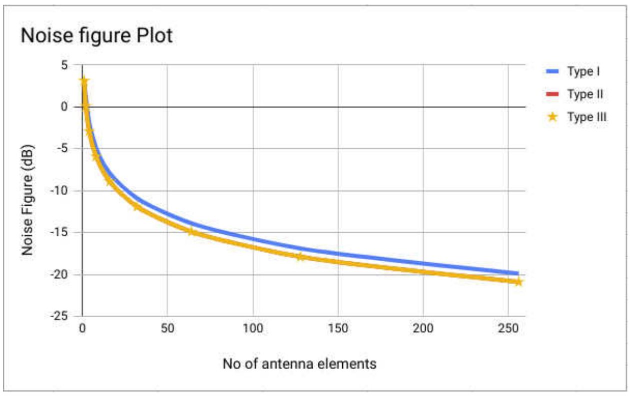


Figure 2. Noise figure variation with number of parallel channels

Noise figure at each block of the receiver system for the three types was calculated and plotted in Figure 3 (a),(b),(c). The overall noise figure is compared with the single channel noise figure value. The overall cascaded gain of the systems is kept uniform for comparison. Gain change with respect to the number of antenna elements are plotted in Figure 4.

(a)

(b)

(c)

Figure 3. Noise figure plot of beamformer configurations (a) Type I, (b) Type II, (c) Type III

It is evident from the plot that the noise figure is better for the case of Type II and Type III. There is no significant difference in noise figure between Type II and Type III from RF point of view. The complexity in the Type III design is compromised by the advantage of digital beamforming and MIMO system.

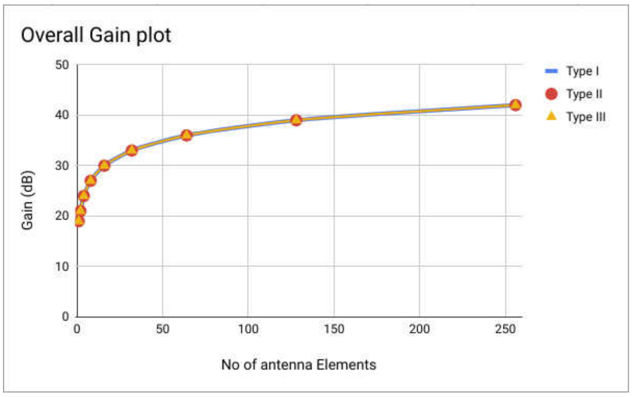


Figure 4. Overall gain variation with antenna elements

4. CONCLUSION

The noise figure value for the fixed beam, analog beamformer and digital beamformer were calculated and presented here. For all the three configurations the improved noise performance comes from the fact that the signal are added coherently and the uncorrelated noise cancel each other. The contribution of noise from RF circuit is low compare to the improvement over coherent addition. The down conversion mixer has negligible effect on the signal chain. Compare to a single channel system the array system offers better gain, directivity, noise performance. The front end LNA offers better noise performance over direct combining (Type -I). The result offers designers the optimum array size and configuration for beamforming system design.

5. Acknowledgements

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7. References

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