Progress In Electromagnetics Research Letters, Vol. 65, 15–21, 2017

A Method for Analyzing Broadcast Beamforming of Massive MIMO Antenna Array

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Abstract—In this paper, a new analysis method of broadcast beamforming for a massive MIMO antenna array, targeting at the fifth generation mobile communication, is introduced. In order to solve the problem of narrow broadcast beam coverage, the element phase of massive MIMO antenna array is optimized using a method, which combines both numerical electromagnetic analysis method and global optimization algorithm. The analysis results show that the optimal value of 3 dB broadcast beam width for 64 antenna elements in the horizontal plane is 36 degree, which is 0.55 times of that of the 4G base station. In addition, the optimal value of gain loss increases to about 13 dB compared with the gain of the antenna fed with equal amplitude and in phase. So it is also necessary to take the system link budget of the broadcast channel into consideration. The proposed analysis method and design solution can provide reference for the research of the next generation mobile communication.

1. INTRODUCTION

With the development of wireless communication technology, the increasing applications of wireless network lead to the increase of wireless data services. This brings great challenges to the wireless access network. So it is urgent to substantially improve the spectrum efficiency in the design of communication system.

Massive MIMO is considered to be the most potential wireless communication technique. It is the expansion and extension of the existing MIMO techniques of the 4G network [3–15]. Nowadays, the 4G cellular network supports simultaneous wireless transfer of maximum 8-ports [16], which is not enough to meet the requirements of future wireless data services. Comparatively, a massive MIMO antenna array (from tens to thousands) with SDMA technique is able to provide services to multiple users with the same time-frequency resource. In 2010, Marzetta from the Bell Laboratory proposed a large MIMO antenna array that could be used in the base station to improve the system capacity greatly [17]. In 2013, 3GPP proposed massive MIMO and MIMO 3D to identify typical scenarios of UE-specific beamforming and massive MIMO, and a comprehensive MIMO massive MIMO study on antenna, frequency calibration, pilot and feedback, RF requirement, etc. is presented in [18].

An accurate algorithm of radiation pattern beamforming [2, 4, 11, 12] for a massive MIMO active antenna system faces new challenges. As one of the core subsystems of massive MIMO, an active antenna has the virtues of high gain, multiple RF channels, high integration, and high spectral efficiency [1, 4, 8]. However, high antenna gain brings narrow beamwidth for broadcast channel, which cannot satisfy the demand for coverage.

This paper aims to improve the situation of narrow broadcast beam coverage of antenna array for massive MIMO application. First of all, a basic model of a 5G massive antenna array is presented.

Received 30 June 2016, Accepted 18 October 2016, Scheduled 20 December 2016
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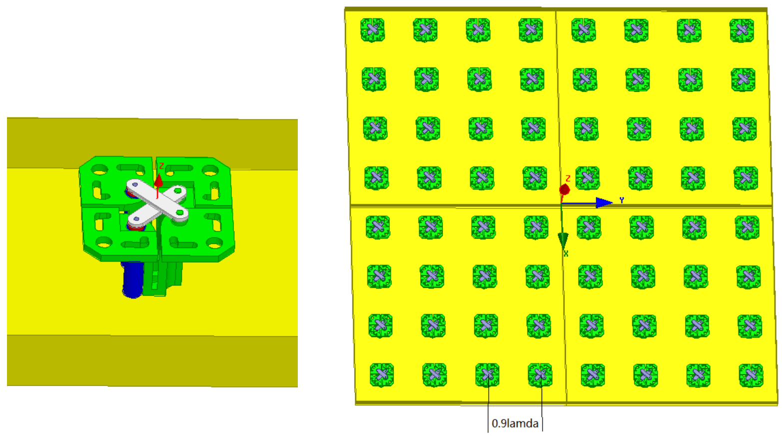
Based on this, the element phase of the antenna array composed of 64 elements is optimized by the design of numerical electromagnetic analysis method and global optimization algorithm. The broadcast beam coverage is maximized with reasonable link budget. The analysis method can be regarded as a reference to solve the problem of narrow broadcast beam coverage.

2. ARCHITECTURE MODEL OF MASSIVE MIMO ANTENNA ARRAY

The models of the massive MIMO antenna element and array are shown in Figs. 1(a) and (b). The antenna element consists of two cross dipoles which achieve $\pm 45°$ polarizations. Four square metal sheets with slots added on are designed as the arms of the dipoles. The size of the antenna is $27.2\,\text{mm} \times 27.2\,\text{mm} \times 17\,\text{mm}$, and the gap between the antenna arms is 0.8 mm. The dipoles are fed by two cross feeding pads, which have the size of $10\,\text{mm} \times 3.2\,\text{mm} \times 0.8\,\text{mm}$.



(a) (b)

Figure 1. Design of the antenna element and the antenna array. (a) Antenna element. (b) 64 elements massive antenna array.

The antenna array consists of 64 elements which operate at the frequency ranging from 3.6 to 4.8 GHz. The two dipoles with the same polarization of the two adjacent antenna elements along the vertical direction share one RF channel. So the number of RF channels to be optimized is 32. Taking the tradeoff between beamforming and correlation coefficient into consideration, the distance between two antenna elements is designed to be 0.9λ, where λ is the wavelength corresponding to the center frequency [19]. The gain of the antenna at the center frequency is 26.8 dBi.

3. BASIC PRINCIPLE

A plane antenna array with multiple RF channels is used for the design of massive MIMO system. Therefore, the design of the plane antenna array should consider the requirements of the broadcast beamforming of traditional linear array, such as gain in horizontal plane, beamwidth, side lobe suppression, and Front-to-Back Ratio (F/B ratio). In addition, in terms of the link budget, the EIRP loss of the massive MIMO system caused by the design of amplitude and phase distribution should also be considered. Hence, the design of broadcast beamforming of the plane antenna array becomes more complicated due to the existence of massive RF channels. On the other hand, more freedoms are brought by the multiple RF channels which increase from 4 degrees of freedom of the traditional broadcast beamforming to more than 32 degrees of freedom. This makes the selection of amplitude and phase distribution more flexible.

A numerical method named Method of Moments (MoM) is used to compute the antenna radiation field. MoM is a relatively mature numerical method. In MoM, the unknown electric and magnetic currents in the electromagnetic integral equation are firstly expressed by the linear combination of a set of basis functions. Secondly, inner product is taken on both sides of the linear equation with proper testing function, which results in a group of linear equations or matrix equation. The solution of the matrix equation can be utilized to obtain the unknown electric and magnetic currents or the spatial distribution of field.

Generally, both the genetic algorithm (GA) and differential evolution (DE) can be used to optimize the design of amplitude and phase. In this study, since the broadcast beamforming does not need to be real-time with high calculation speed, traditional GA is selected to optimize the design. GA is an adaptive global optimization algorithm of probability search which simulates the genetic and evolutionary process of organisms in natural environment. It provides a general framework for solving the optimization problem of complex systems, which does not depend on the specific domain of the problem and has a strong robustness for various problems.

4. BROADCAST BEAM DESIGN OF MASSIVE ANTENNA ARRAY

The design of broadcast beamforming of a 5G massive antenna array should consider three aspects, radiation pattern in horizontal plane, radiation pattern in vertical plane and EIRP. To simplify the design process, the amplitudes of the antenna elements are fixed to be equal, and only the phases are optimized. Thus, the consideration of system index EIRP is equivalent to that of the gain loss of radiation pattern. The simplified indexes consist of gain loss (compared with the gain of the antenna array fed by equal amplitude and in phase), downtilt angle in vertical plane, first side-lobe suppression in vertical plane, null filling in vertical plane, global side-lobe suppression in vertical plane, and 3 dB beamwidth in horizontal plane. The antenna array that requires broadcast beamforming is displayed in Fig. 1, and parameter to be optimized is the phase value of 32 RF channels.

The optimization model of beamforming is established as:

$$\begin{cases} \min(G_{reduce}(\mathbf{x})) \\ \theta(\mathbf{x}) = \theta_0 \\ sls(\mathbf{x}) \leq sls_0 \\ null(\mathbf{x}) \geq null_0 \\ gsls(x) \leq gsls_0 \\ HPBW(\mathbf{x}) = HPBW \\ x_{n,\min} \leq x_n \leq x_{n,\max}, \quad n = 1, \ldots, N \end{cases} \tag{1}$$

where $G_{reduce}(\mathbf{x})$ is the gain loss, $\theta(\mathbf{x})$ the downtilt angle in vertical plane, $sls(\mathbf{x})$ the side lobe suppression in vertical plane, $null(\mathbf{x})$ the null filling in vertical plane, $gsls(x)$ the global side lobe suppression in vertical plane, and $HPBW(\mathbf{x})$ the beamwidth in horizontal plane. The sub objective functions of optimization are:

$$\begin{cases} m_1(x) = \theta(\mathbf{x}) - \theta \\ m_2(\mathbf{x}) = sls_0 - sls(\mathbf{x}) \\ m_3(\mathbf{x}) = null(\mathbf{x}) - null_0 \\ m_4(\mathbf{x}) = gsls_0 - gsls(x) \\ m_5(\mathbf{x}) = HPBW(\mathbf{x}) - HPBW \end{cases} \tag{2}$$

According to the above requirements, the general objective function of design is:

$$F(x) = a_1 G_{reduce}^2(x) + a_2 m_1^2(x) + a_3 \max{}^2[-m_2(x), 0] + a_4 \max{}^2[-m_3(x), 0] + a_5 \max{}^2[-m_4(x), 0] + a_6 m_5^2(x) \tag{3}$$

To begin with, the radiation pattern in horizontal and vertical planes of the antenna array composed of 64 antenna elements is calculated with feed of equal amplitude and in phase, which can be utilized as a reference of the following beamforming. As shown in Fig. 2, V is an indication of the radiation pattern in vertical plane while H illustrates the radiation pattern in vertical plane. It is shown that the radiation patterns in horizontal and vertical plane are completely symmetrical because of the array symmetry. The angle of main-lobe direction is 0°. Side-lobe suppression in vertical plane is 13.8 dB, and the 3 dB beamwidth in horizontal plane is 6.5°.

Because of the high gain, broadcast beam coverage of the massive antenna array becomes narrow. So the main target of beamforming design is to increase the 3 dB beamwidth of broadcast beam in horizontal plane. The 3 dB broadcast beamwidths of 8 and 15 degrees in horizontal plane are shown

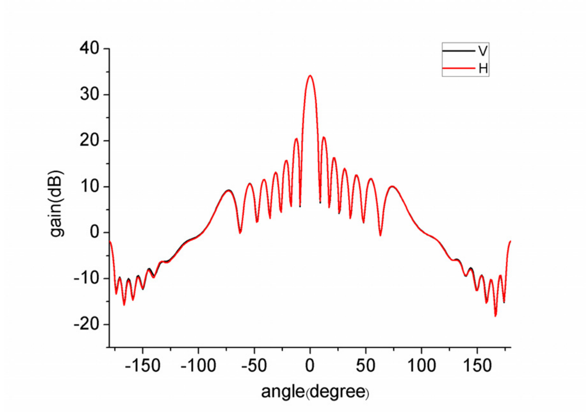


Figure 2. The radiation patterns of broadcast beam of equal amplitude and in phase in horizontal and vertical plane.

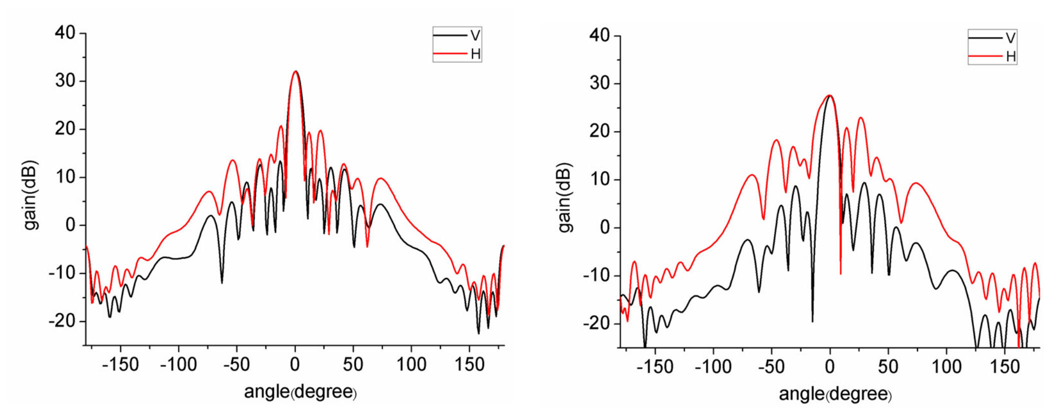
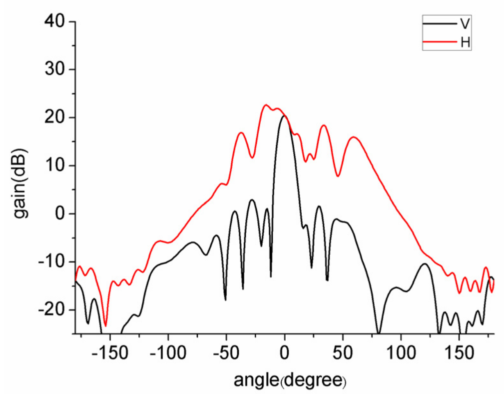


Figure 3. The radiation pattern of broadcast beam. (a) 8 degree of 3 dB beamwidth in horizontal plane. (b) 15 degree of 3 dB beamwidth in horizontal plane.

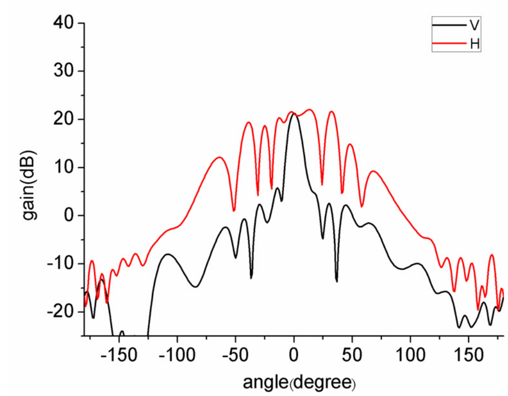
in Fig. 3, where V indicates the radiation pattern in vertical plane while H represents the radiation pattern in horizontal plane. It can be seen that in the case of 3 dB beamwidth in horizontal plane being 8 degrees, the side-lobe suppression in vertical plane is 18.72 dB, null filling in vertical plane 30.71 dB, angle of main-lobe direction in vertical plane 0 degree, global side-lobe suppression in vertical plane 18.72 dB, and gain loss 2.06 dB. In the situation of 3 dB beamwidth in horizontal plane being 15 degrees, the side-lobe suppression in vertical plane is 24.30 dB, null filling in vertical plane 26.58 dB, angle of main lobe direction 0 degree, global side-lobe suppression in vertical plane 18.22 dB, and gain loss 6.59 dB.

Figure 4 exhibits the radiation pattern of the broadcast beam of 25 and 35 degrees of 3 dB beamwidth in horizontal plane. It can be seen from the figure that in the case of 3 dB beamwidth in horizontal plane being 25 degrees, the side-lobe suppression in vertical plane is 19.36 dB, null filling in vertical plane 23.43 dB, angle of main-lobe direction 0 degree, global side-lobe suppression in vertical plane 17.55 dB, and gain loss 13.74 dB. In the situation of 3 dB beamwidth in horizontal plane being 35 degrees, the side-lobe suppression in vertical plane is 15.49 dB, null filling in vertical plane 26.03 dB, angle of main-lobe direction 0 degree, global side-lobe suppression in vertical plane 15.48 dB, and gain loss 12.93 dB.

Figure 5 exhibits the radiation pattern of the broadcast beam of 45 degrees of 3 dB beamwidth in horizontal plane. It can be seen that the side-lobe suppression in vertical plane is 12.35 dB, null filling in vertical plane 20.22 dB, angle of main-lobe direction 7 degrees, global side-lobe suppression in vertical



(a)



(b)

Figure 4. The radiation pattern of broadcast beam. (a) 25 degree of 3 dB beamwidth in horizontal plane. (b) 35 degree of 3 dB beamwidth in horizontal plane.

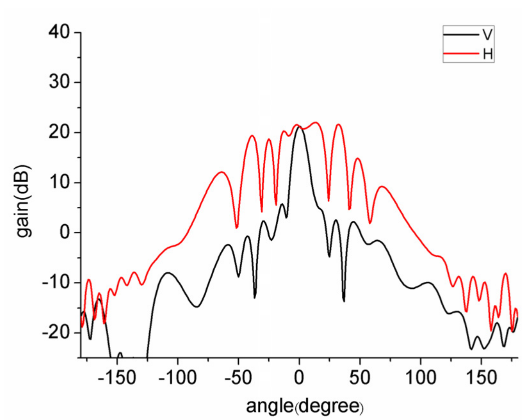


Figure 5. The broadcast beamforming pattern of 45 degree of 3 dB beam width in horizontal plane.

Table 1. Statistical results of beamforming with 3 dB beamwidth in horizontal plane as the main optimization goal.

	Upper side lobe suppression in vertical plane (dB)	Null filling in vertical plane (dB)	Direction of main lobe (degree)	Global side lobe suppression in vertical plane (dB)	Gain loss (dB)	3 dB beamwidth in horizontal plane (degree)
Beamforming 1	13.8	/	0	13.8	0	6.5
Beamforming 2	18.72	30.71	0	18.72	2.06	8
Beamforming 3	24.30	26.58	0	18.22	6.59	15
Beamforming 4	19.36	23.43	0	17.55	13.74	25
Beamforming 5	15.49	26.03	0	15.48	12.93	36
Beamforming 6	12.35	20.22	7	10.16	8.73	44

plane 10.16 dB, and gain loss 8.73 dB.

It is implicated by the above simulation results that the antenna gain is decreased with the increase of 3 dB beamwidth. When the side-lobe level is raised to the same level as the main lobe, it is difficult to increase the beamwidth of the broadcast beam by optimizing the phase distribution. Therefore, in practical applications, when the total output power is constant, the broadcast beam can be optimized using the joint optimization of the amplitude and phase.

5. CONCLUSION

On the basis of the above beamforming design, statistical results of relevant indexes are listed in Table 1, where beamforming 1 represents the result in the case of each element excited by equal amplitude and in phase. Beamforming 2–6 are sequentially arranged with the increase of 3 dB beamwidth in horizontal plane. It can be known that with the increase of 3 dB beamwidth in horizontal plane, the gain loss of the massive antenna array becomes greater. The maximum gain loss reaches approximately 13 dB. The upper side-lobe suppression, null filling, and side-lobe global suppression in vertical plane have reasonable values at beamforming 2–5. When 3 dB beamwidth in horizontal plane is increased to 45 degrees, the main-lobe direction deviates from the expectation angle (0 degree) to 7 degrees, which does not meet the requirement of application. As a result, for the design of broadcast beamforming of a 5G massive antenna array, the optimized value of 3 dB beamwidth in horizontal plane is about 36 degrees, which is roughly 0.55 times of that of a 4G base station antenna. The broadcast beam coverage becomes smaller. The gain loss increases up to about 13 dB, and the link budget of broadcast channel should obtain more attention.

REFERENCES

1. Marcus, M. J., "5G and IMT for 2020 and beyond," *Spectrum Policy and Regulatory Issues. IEEE Wireless Communications*, Vol. 22, No. 4, 2–3, 2015.
2. Liu, G. and D. Jiang, "5G: Vision and requirements for mobile communication system towards year 2020," Vol. 2016, 1–8, 2016.
3. Lu, L., G. Y. Li, A. L. Swindlehurst, et al., "An overview of massive MIMO: Benefits and challenges," *IEEE Journal of Selected Topics in Signal Processing*, Vol. 8, No. 5, 742–758, 2014.
4. Li, Y., et al., "An enhanced beamforming algorithm for three dimensional MIMO in LTE-advanced networks," *2013 International Conference on Wireless Communications & Signal Processing (WCSP)*, 1–5, 2013.
5. Yilmaz, O. N. C., S. Hämäläinen, J. Hämäläinen, "Analysis of antenna parameter optimization space for 3GPP LTE," *IEEE Vehicular Technology Conference Fall*, 1–5, 2009.
6. Pang, X., W. Hong, T. Yang, et al., "Design and implementation of an active multibeam antenna system with 64 RF channels and 256 antenna elements for massive MIMO application in 5G wireless communications," *Wireless Communication Over Zigbee for Automotive Inclination Measurement China Communications*, Vol. 11, 16–23, 2014.
7. Hoydis, J., S. Ten Brink, and M. Debbah, "Massive MIMO: How many antennas do we need," *2011 49th Annual Allerton Conference on Communication, Control, and Computing (Allerton)*, 545-550, IEEE, 2011.
8. Nam, Y. H., et al., "Full-dimension MIMO (FD-MIMO) for next generation cellular technology," *IEEE Communications Magazine*, Vol. 51, 172–179, 2013.
9. Ma, R., et al., "Dual-polarized turning torso antenna array for massive MIMO systems," *IEEE European Conference on Antennas and Propagation*, 2015.
10. Panzner, B., et al., "Deployment and implementation strategies for massive MIMO in 5G," *2014 IEEE Globecom Workshops (GC Wkshps)*, 346–351, 2015.
11. Niyato, D., et al., "Competitive cell association and antenna allocation in 5G massive MIMO networks," *IEEE International Conference on Communications*, 2015.

12. Gao, X., et al., "Antenna selection in measured massive MIMO channels using convex optimization," *2013 IEEE Globecom Workshops (GC Wkshps)*, 129–134, 2013.
13. Jin, S., et al., "Zero-forcing beamforming in massive MIMO systems with time-shifted pilots," *IEEE International Conference on Communications*, 4801–4806, 2014.
14. Qu, Y., G. Liao, S.-Q. Zhu, X.-Y. Liu, and H. Jiang, "Performance analysis of beamforming for MIMO radar," *Progress In Electromagnetics Research*, Vol. 84, 123–134, 2008.
15. Mouhamadou, M., P. Vaudon, and M. Rammal. "Smart antenna array patterns synthesis: Null steering and multi-user beamforming by phase control," *Progress In Electromagnetics Research*, Vol. 60, 95–106, 2006.
16. Xiao, Y., et al., "Performance analysis of smart antenna array with mono-and dual-polarization in TD-LTE system," *Journal of China Academy of Electronics and Information Technology*, 151–154, 2010.
17. Marzetta, T. L., "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Wireless Communications*, Vol. 9, No. 11, 3590–3600, Nov. 2010.
18. Shepard, C., H. Yu, N. Anand, L. E. Li, T. L. Marzetta, R. Yang, and L. Zhong, "Argos: Practical many-antenna base stations," *Proc. ACM Int. Conf. Mobile Computing and Networking (MobiCom)*, Aug. 2012.
19. Yatskevich, V. and Y. Bulikov, "Method of eliminating interference noughts of radiation pattern of base station antenna array," 2003.