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5G evolution promoting innovation of antenna systems*

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Abstract: We introduce the basic concept, background, and development of mobile communication systems from the first generation (1G) to the fifth generation (5G) including their antenna systems. We also describe the requirements for 5G networking and optimization of antenna systems, and present the basic principle of three-dimensional array antennas. Weight optimization methods of massive multiple-input multiple-output (MIMO) antennas are proposed and verified. Finally, several ideas are given to solve the problem of power consumption of 5G antenna systems.

Key words: Fifth generation (5G); Massive multiple-input multiple-output (MIMO) antenna array; Power consumption; Weight optimization

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1 Introduction

In the past 30 years, wireless communication has achieved a tremendous success in the global market. Even after decades of fast growth, there is a steady increase in the number of cellular devices manufactured, which surpasses the population in some countries because of consumers' need to stay connected wirelessly. For instance, since China Mobile commercially launched Time Division-Synchronous Code Division Multiple Access (TD-SCDMA) 3G in 2009 and Time Division-Long Term Evolution (TD-LTE) in 2013, statistics showed that there had been almost a billion subscribers by October 2018 (Noble, 1962; Donald, 2014).

The original, voice-only wireless telephone technology is the first generation (1G). In 1G, the receiver end employed thin rod-based extendable monopole antennas. In the second generation (2G), the initial antenna technologies used in its base stations were single-polarized omnidirectional or directional antennas. Then, dual-polarized antennas with remote electrical downtilt were implemented. In 2000, the third generation (3G) was introduced. The smart antenna of the TD-SCDMA system was initially applied in mobile communication. China Mobile was the only operator of the TD-SCDMA system in the world, and it promoted the development of Time Division Duplex (TDD) technology (Basavarajappa, 2018). Long-Term Evolution (LTE) is commonly referred to as advanced fourth generation (4G) or 4G LTE, and the multiple-input multiple-output (MIMO) technology is one of the two key techniques of LTE. Based on the TD-LTE technology, China Mobile has applied the 3D-MIMO technology, which is also called pre-5G. To achieve 1000 times capacity gain and 10 Gb/s of speed in 5G, massive MIMO antenna systems have become the key in wireless systems (Hoydis et al., 2013; Chen SZ et al., 2015). The evolution of the mobile communication antenna is illustrated in Fig. 1.

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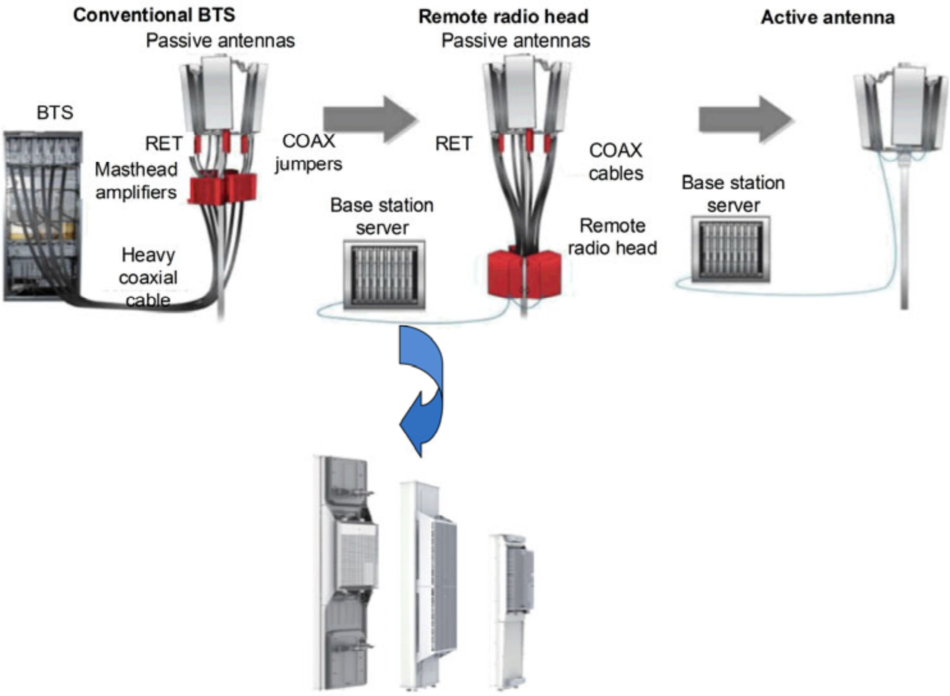

Fig. 1 Evolution of the mobile communication antenna (Chen LP, 2015)
BTS: base transceiver station; RET: remote electrical tilt

2 Requirements of 5G for antenna systems

China Mobile's 5G networking modes are standalone (SA) and non-standalone (NSA), which coexisted in 2019, with SA focusing on meeting the industry's vertical application requirements. At first, FDD1800 was considered to be an NSA anchor, followed by TDD F band (Fig. 2).

2.1 5G networking to antenna systems

According to Shannon's formula, there is

$$C = B\log_2\left(1+\frac{S}{N}\right), \tag{1}$$

where C is the channel capacity, B the bandwidth (Hz), S the signal power (W), and N the noise power (W). Shannon's formula can be further expressed using the formula shown in Fig. 3.

By the time when 5G encoding and decoding processes would reach a capacity limit, antenna systems would be a key for improving the capacity of 5G networks. Compared with beamforming to a single user, most massive MIMO (MM) antennas have the ability to multiplex to multiple users, which can improve the spectrum utilization (Nadeem et al., 2018).

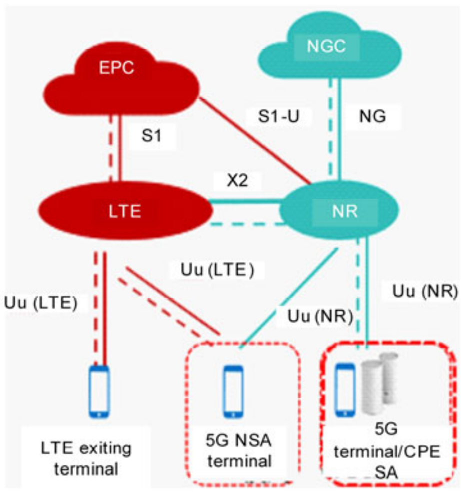

Fig. 2 5G network architecture
EPC: evolved packet core; LTE: long-term evolution; NGC: next-generation core; NG: next generation; CPE: customer premise equipment; NR: new radio; SA: standalone; NSA: non-standalone

Because the speed of 5G is high, two systems are used: one is the wide frequency band and the other is the MM antenna. Compared with 4G three-dimensional

MIMO (3D-MIMO), the coverage ability of the broadcast control channel of the 5G MM antenna is stronger. Six narrow beams are used in a horizontal plane, and the coverage range is improved to 2–4 dB; two wide beams are used to improve the coverage range in a vertical plane compared with 4G 3D-MIMO.

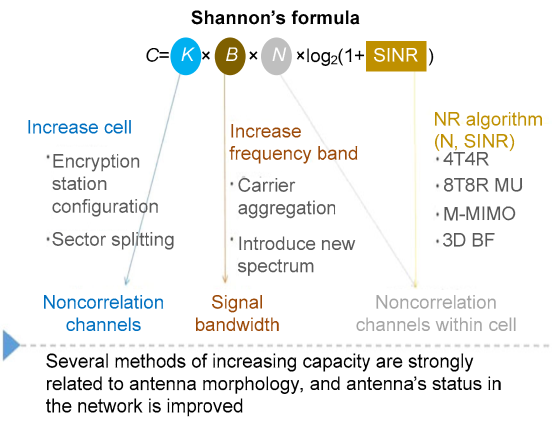

Fig. 3 Capacity factors of Shannon's formula

With the introduction of 5G communication systems, antenna systems transformed from passive to active, more intelligent, and more miniaturized. The 5G MM antenna system not only has dipole antennas and calibrated networks, but also includes radio frequency (RF) active devices such as power amplifiers and filters. With this, more systematic and integrated antenna designs would be required. Integration design of performances such as large-scale antenna arrays, 3D-MIMO, and low loss, can help the signal processing of baseband and radio frequency systems achieve the corresponding efficiencies.

The core requirements for 5G MM antennas are miniaturization (space reduction), low profile, light weight, multi-device integration (antenna on package, AoP), and over-the-air self-calibration. Typical examples include the lens antenna array based on super-material, magnetic dipole antenna, holographic beamforming antenna, and solid-state plasma antenna array (Fig. 4). Among them, the lens antennas with super-materials are applied in 5G, studied in the China Mobile R&D Center of Network Design and Optimization.

2.2 5G massive MIMO antenna array

In a 3D MM antenna array, the antenna pattern is not only determined by the weight vector of the array elements, but also affected by the inductive signals on each array element, which is different from the common antenna array.

The matrix factor is given by

$$\begin{aligned}\boldsymbol{E}(\theta,\phi)=\sum_m\sum_n\left|\boldsymbol{a}_{mn}\right|\exp\big\{\mathrm{j}\big[(m\mathrm{d}x+\Delta n)\\ \cdot k(u-u_0)+n\mathrm{d}yk(v-v_0)\big]\big\},\end{aligned} \tag{2}$$

where m and n are numbers of rows and columns of the antenna array respectively, θ is the angle between the direction of arrival and the z axis, ϕ is the angle between the direction of arrival and the x axis, u and v are the electric potentials in x and y directions respectively, u_0 and v_0 are initial potentials in x and y

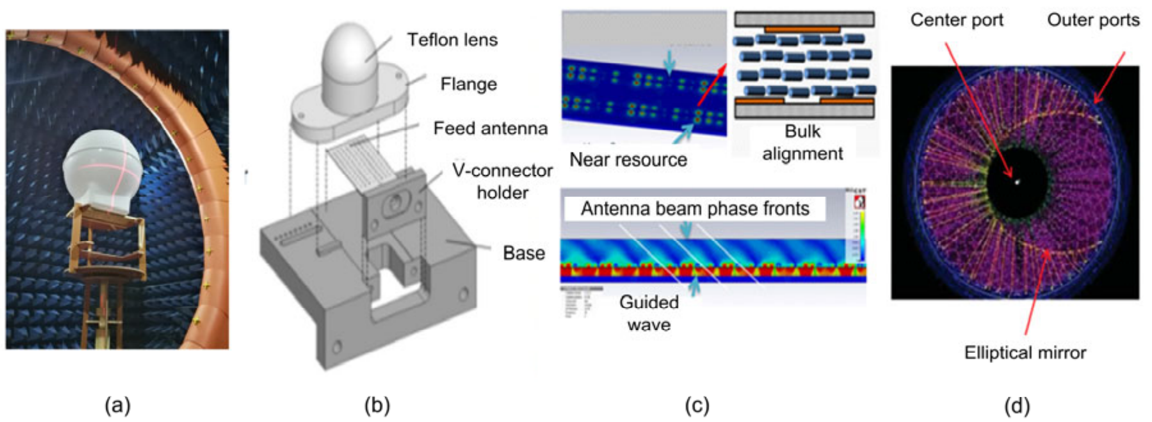

Fig. 4 New types of 5G massive MIMO antenna: (a) lens antenna with super-material; (b) integrated lens antenna; (c) holographic beamforming antenna; (d) solid-state plasma antenna (Zhao et al., 2017)

directions respectively, and dx and dy are differentials of x and y respectively. $\Delta n=nd/(\lambda\cos\theta)$ is the phase difference caused by the space wave path difference, where λ is the wavelength and d the array spacing. In addition, $k=2\pi/\lambda$. For a 5G antenna array, the amplitude distribution $\boldsymbol{a}_{mn}$ can be separated. Assuming the induction signal component at each element is a stationary process with an average value of zero, then the radiation pattern of the antenna array can be calculated by the conditional mathematical expectation of $P(\theta, \phi, t)$ given the weight vector $\boldsymbol{W}$.

The 3D module of an MM antenna array can be expressed below:

$$\begin{aligned} P(\theta,\phi) &= E[P(\theta,\phi,t)] \\ &= P_{\mathrm{E}}^{2}(\theta,\phi)\tilde{\boldsymbol{W}}^{\mathrm{H}}E[\boldsymbol{S}(t)\boldsymbol{S}^{\mathrm{H}}(t)]\tilde{\boldsymbol{W}} \\ &= P_{\mathrm{E}}^{2}(\theta,\phi)\tilde{\boldsymbol{W}}^{\mathrm{H}}\boldsymbol{R}\tilde{\boldsymbol{W}}, \end{aligned} \tag{3}$$

where $\tilde{\boldsymbol{W}}$ is the conjugate of $\boldsymbol{W}$ and $\boldsymbol{S}(t)$ is composed of m elements (i.e., $s_1, s_2, \ldots, s_m$).

Given the correlation coefficients ρ and considering model simplification, the correlation coefficient matrix $\boldsymbol{R}$ can be expressed as

$$\boldsymbol{R}=E[\boldsymbol{S}(t)\cdot\boldsymbol{S}^{\mathrm{H}}(t)]=\begin{bmatrix} 1 & \rho & \cdots & \rho \\ \rho & 1 & \cdots & \rho \\ \vdots & \vdots & & \vdots \\ \rho & \rho & \cdots & 1 \end{bmatrix}. \tag{4}$$

Then the pattern model of an MM antenna array can be simplified as follows:

$$\begin{aligned} P(\theta,\phi) &= \frac{\rho}{N}P_{\mathrm{E}}^{2}(\theta,\phi)\left|\sum_{i=1}^{N}v_i\right|^2+(1-\rho)P_{\mathrm{E}}^{2}(\theta,\phi) \\ &= P_{\mathrm{E}}^{2}(\theta,\phi)\left[1+\rho\left(\left|\sum_{i=1}^{N}v_i\right|^2\Big/(N-1)\right)\right]. \end{aligned} \tag{5}$$

2.3 Weight optimization of a massive MIMO antenna array

The MM antenna introduces more dimensionally adjustable parameters to cover multiple scenarios, making 5G optimization more complex. The traditional way is no longer applicable. An intelligently optimized method is needed to realize the artificial intelligence (AI) optimization for the 5G network.

The targets of weight optimization include decreasing the interference and improving the throughput and user satisfaction. First, the hot spots, e.g., the central business district (CBD), residential areas, and schools, are located through the AI technology, and different scenarios can be identified. Second, 3D map grid is implemented based on the minimization of drive tests data of the 4G/5G shared antenna and 5G beam data of user distribution. Third, the sample library of weights is determined using a machine learning algorithm, the K-nearest neighbor (KNN) algorithm.

When data accumulation reaches a certain proportion, a more efficient differential evolution (DE) iteration algorithm can be used to achieve unit-level joint weight adjustment. According to the user equipment (UE) distribution in different scenarios, the antenna weight self-optimizing configuration can be adjusted dynamically to replace part of the work of traditional manual network planning and optimization.

The DE algorithm is a stochastic optimization algorithm based on population, using N d-dimensional parameters (i=1, 2, …, N; j=1, 2, …, D) to parallelly and directly search in the search space. Here, N is the population size and D is the number of decision variables. The basic operations of standard DE include mutation, crossover, and selection. To verify the accuracy of the coverage optimization algorithm for a 5G MM antenna array, the optimized target function is set as

$$\begin{aligned} E=\min\Bigg\{ & \alpha\frac{1}{N}\sum_{1}^{N}[f(i)-f_T(i)]^2 \\ & +\beta\{f(\theta_0)-\max[f(j)]\}^4+\gamma E'+\tau E''\Bigg\}, \end{aligned} \tag{6}$$

where α, β, γ, and τ are weight factors constraining the main beam, beam direction, sidelobe, and weight efficiency respectively, and $f(x_1, x_2, \ldots, x_n)$ is the nonlinear target function.

Table 1 shows the suggestion of broadcast patterns in different scenarios. Generally, pattern 1 is recommended when applying the scenario of a typical 3-sector. If a large horizontal coverage is required, scenario 8, 9, or 10 is recommended. In this case, higher beam gains can be obtained at the cell edge, and the coverage range can be improved. If a fixed interference source exists at the cell edge, scenario 2 or 3 can be used to narrow the horizontal coverage range and reduce the inference.

Given isolated buildings, scenario 4, 5, 6, or 7 is recommended to provide a small horizontal coverage. These scenarios, however, are not suitable for continuous networks.

Either scenario 1 or 8 should be selected for low-rise buildings. For middle-rise buildings, one from scenarios 2, 4, and 9 can be selected, while for high-rise buildings, one from scenarios 3, 5, 6, 7, and 10 can be chosen.

The purposes of weight optimization and beam management are to properly design narrow beams and to select appropriate time-frequency resources to transmit narrow beams. Table 2 shows three different configurations of broadcast beams. In the condition with eight beams, the horizontal half power beam width (HPBW) of the sub-beam series is [16°, 10°, 10°, 10°, 10°, 10°, 10°, 16°], the direction of the sub-beam series is [−29°, −20°, −12°, −4°, 4°, 12°, 20°, 29°], and the sub-beam vertical HPBW is 6°.

The eight-beam disposition is applied for common scenarios for macro coverage and low-floor coverage. Two kinds of new radio (NR) broadcast beam configurations are optimized and simulated using a commercial 3D electromagnetic field analysis software ANSYS HFSS. Fig. 5 shows the coverage in the square scenario. The wide beams are used at the cell center to ensure access, and the narrow beams are

Table 1 Broadcast beam patterns in different scenarios

Pattern	Horizontal HPBW (°)	Vertical HPBW (°)	Azimuth (°)	Digital beam tilt (°)	Application scenario
1	65	6	[−10, +10]	[−3, +12]	Standard macro coverage and low-floor coverage
2	65	12	[−10, +10]	[−3, +12]	Standard macro coverage and middle-floor coverage
3	65	25	[−10, +10]	[+9, +12]	Standard macro coverage and high-floor coverage
4	45	12	[−20, +20]	[−3, +12]	Middle buildings and hotspot coverage
5	45	25	[−20, +20]	[+9, +12]	High buildings and hotspot coverage
6	30	25	[−30, +30]	[+9, +12]	High buildings and hotspot coverage
7	15	25	[−40, +40]	[+9, +12]	High buildings and hotspot coverage
8	90	6	0	[−3, +12]	Standard macro coverage and low-floor coverage
9	90	12	0	[−3, +12]	Standard macro coverage and middle-floor coverage
10	90	25	0	[+9, +12]	Standard macro coverage and high-floor coverage

HPBW: half power beam width

Table 2 Different configurations of broadcast channel narrow beams

Broadcast beam	subBeam index	Azimuth (°)	Downtilt (°)	Horizontal HPBW (°)	Vertical HPBW (°)
Single beam	1	0	6	65	6
Four beams	0	−27	6	20	6
	1	−9	6	20	6
	2	9	6	20	6
	3	27	6	20	6
Eight beams	0	−29	6	16	6
	1	−20	6	10	6
	2	−12	6	10	6
	3	−4	6	10	6
	4	4	6	10	6
	5	12	6	10	6
	6	20	6	10	6
	7	29	6	16	6

HPBW: half power beam width

used at the cell edge to improve the coverage range. Fig. 6 shows the coverage in a high-rise building scenario. The beams with a wide vertical coverage are used to improve the vertical coverage range.

Beam parameter optimization includes weight initialization and weight optimization. Fig. 7 shows the weight optimization flowchart. The input of the system is network data, such as measure reports and electronic map data. The weight optimization threshold evaluation reduces the optimized cell range and focuses on beam issues.

The key techniques of this system include weight library construction, user hotspot clustering, and spatial scene recognition. The spatial clustering technology enables automatic user hotspot discovery and automatic scene recognition.

2.4 Problems in power consumption of 5G antenna systems

Different factories have different equipment forms and parameters. For 5G equipment, some equipment bandwidth is 160 MHz and some is 100 MHz; some equipment power is 240 W and some is 200 W. Its power consumption is far greater than that of 4G devices in the pre-commercial test of China Mobile.

The power consumption of the 5G base station in the test network is about 2.5–3.5 times that of the 4G base station. The full-load power of a 5G base station is nearly 3700 W, which is necessary to plan the power supply and supporting system in advance. It not only challenges the distribution of power in the communication workshop, but also puts forward high requirements for the expansion of power supply. Table 3 shows the power consumption of 4G and 5G equipment under different load conditions.

The power consumption of 5G equipment comes mainly from the active antenna unit (AAU), and the power amplifier consumes the most power in an AAU.

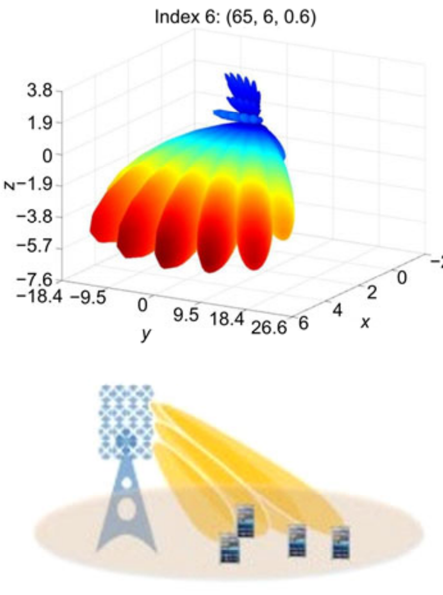

Fig. 5 New radio broadcast beams in square scenarios

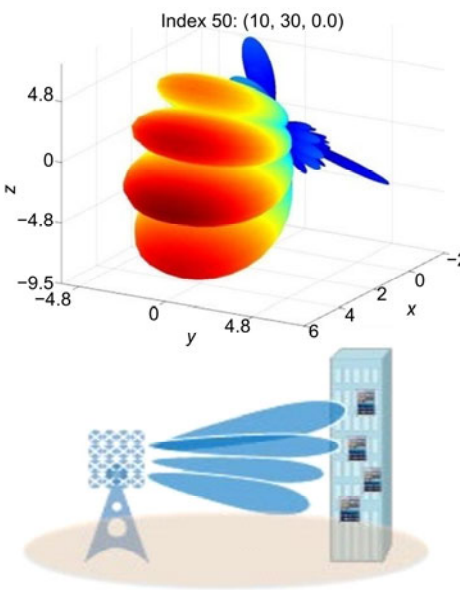

Fig. 6 New radio broadcast beams in high-rise buildings

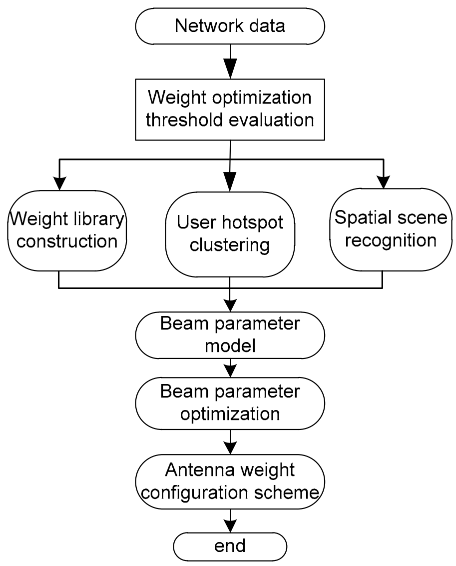

Fig. 7 Weight optimization flowchart

Table 3 Power of 4G/5G under different conditions

Load (%)	Power (W)		Power ratio (5G/4G)
	4G	5G	
100	1044.72	3674.85	3.5
50	995.06	2969.97	3.0
30	949.22	2579.83	2.7
Empty	837.21	2192.57	2.6

Compared with a 4G remote radio unit (RRU), a 5G AAU has 10 times more channels and more than five times larger bandwidth. Therefore, manufacturers should improve the efficiency of the power amplifier and reduce the power consumption from the source by improving the algorithm capability and adopting more advanced power amplifier technologies.

Many factors such as RF devices, equipment, base stations, and network dimensions should be studied to reduce the 5G power consumption. China Mobile's 2.6-GHz spectrum can be shared by 4G and 5G equipment. The 4G system can be loaded in reverse at the 2.6 GHz frequency band of a 5G AAU module. If the original 8-channel D-band module is removed, the power consumption can be effectively reduced for 5G base stations. Based on multi-frequency multi-network cooperative energy conservation, when adopting intelligent energy-saving technologies such as symbol shutdown, carrier shutdown, channel shutdown, and deep dormancy for low-load scenarios, 2G/4G/5G cooperative energy-saving can be achieved. For example, the China Mobile Network Department and Design Institute used intelligent power-saving technologies through the intelligent parameter management module on the network large-data platform.

3 Conclusions

We have reviewed the development of communication systems from 1G to 5G and the evolution of requirements of mobile communication systems for antenna systems. Particularly, in the 5G era, MM antenna systems become the key technology. The AAU solution has been presented, and the basic principle and related theory of the 3D antenna array have been elaborated in detail. New requirements of 5G mobile communication system networking and optimization for the antenna system have been recommended. Weight optimization would be implemented by the MM antenna array, and it would obviously improve the quality of test network. However, the improvement in the performance of the 5G system will also bring a significant increase in the power consumption. The 5G MM antenna arrays can potentially reduce uplink and downlink transmit powers through coherent combination and an increased antenna aperture.

Contributors

Feng GAO designed the research. Feng GAO, Peng GAO, and Wen-tao ZHU processed the data. Feng GAO wrote the first draft of the manuscript. Wen-tao ZHU, Chen-xi ZHANG, and Xian-kun MENG helped organize the manuscript. Feng GAO, Peng GAO, and Run-hong SHAN revised and edited the final version.

Compliance with ethics guidelines

Feng GAO, Peng GAO, Wen-tao ZHU, Chen-xi ZHANG, Xian-kun MENG, and Run-hong SHAN declare that they have no conflict of interest.

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