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6G White Paper on Metamaterials for Information Technology

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content

1 Introduction

Metamaterials were first proposed in 1968. Since then, they have received extensive attentions. In the English word of “metamaterial”, the prefix “meta” means beyond and exceed, emphasizing the fact that metamaterials have many properties natural materials do not have. Note that those “meta” properties are not due to the innate physical or chemical properties of materials themselves, but rather the results of engineered novel structures which allow them to possess certain capabilities that transcend natural materials. Because of these, metamaterials are widely used in the fields of optics, acoustics, heat, electromagnetics, and structural mechanics.

Electromagnetic metamaterials (hereinafter shortened as metamaterials) are designed and manufactured according to electromagnetic requirements. Hence, they are also called artificial electromagnetic media. Metamaterials consist of well-arranged artificial microstructures following certain rules (periodic or aperiodic). Each microstructure is composed of dielectric materials or dielectric materials plus metals, with the size at subwavelength level (0.1 - 0.5 wavelengths).

At the beginning, the design of metamaterials followed the concept of equivalent medium which led to the earliest proposed materials that had characteristics of negative refractive index and negative Doppler to be used in scenarios such as radar stealth. They marked an important stage of electromagnetics and materials science. However, equivalent medium metamaterials have three-dimensional structures that are thick and difficult to process, which significantly limits their engineering applications. Later on, the concept of metamaterials was proposed and generalized where other artificially-made structures were also included in the big family of metamaterials. In particular, metasurface is a type of two-dimensional structure composed of subwavelength planar units. It has the advantages of low profile, low cost, and easy processing compared with equivalent medium metamaterials, thus has attracted a lot of attention and finds its wide use in the field of electromagnetics. In addition, the traditional electromagnetic band gap (EBG) structure, frequency selective surface (FSS), and artificial magnetic conductor (AMC) are often considered as the generalized of metasurfaces.

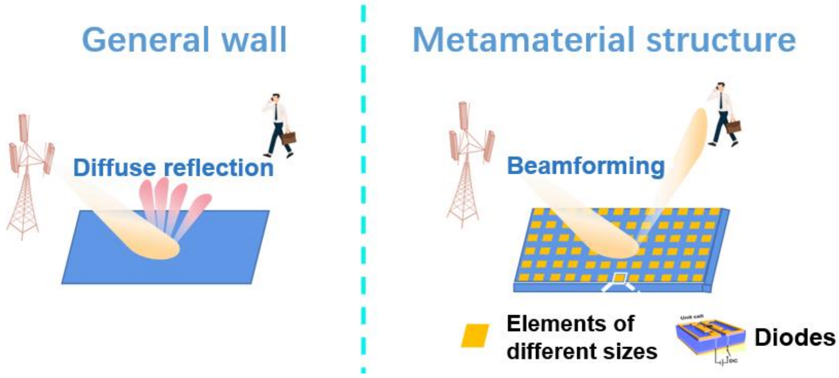

Figure 1. Principles of Metamaterials

While the traditional metamaterials can be used to achieve the control of electromagnetic waves via parameter adjustment of the unit structure, their properties would be fixed once been manufactured, making it difficult for further adjustment. In 2014, a team at Southeast University led by Prof. CUI Tiejun became the first in the world to propose the concept of digital metamaterials, and demonstrated the first field-programmable metamaterial that can adjust the on-off of the diode switch inside the metasurface unit according to the output sequence from FPGA. The direct control of electromagnetic waves in physical space [1] set a precedence for the research on digital programmable metamaterials, and quickly attracted world-wide attention. Since then, varactors, triodes, MEMS, liquid crystals, graphene, phase-change materials, etc. have been introduced to the research on metasurface, together with more diverse control methods to flexibly adjust the amplitude, the phase, the polarizations, etc. Subsequently, Prof. CUI Tiejun proposed the concept of information metamaterials by merging the studies in the fields of information technology, electronics, material sciences and expanded the research on metamaterials from simple spatial-domain coding to space-time-frequency domains joint coding which can be used to directly modulate the spatial-domain electromagnetic information [2,3]. This series of work is of milestone importance in the sense that it has opened a new paradigm to connect the digital world and the physical world, and laid the foundation for the research on information metamaterial-based next-generation wireless communication systems

In July 2021, China Mobile and the Institute of Electromagnetic Space Science and Technology of Southeast University jointly carried out the industry’s first field trial on intelligent metasurface in a commercial 5G network. The results show that the intelligent metasurface can flexibly direct the wave beam according to the distribution of users, thus significantly improving the signal strength, network capacity and data rate in poor coverage areas. The trial adds more confidence regarding the wide application of information metamaterial technology in future wireless communications.

This white paper presents four major applications of information metamaterials: antennas, intelligent reflective surfaces, metasurface based base stations for beamforming, and metasurface-based direct modulations, with the aim to share new design concepts and technical means for 6G communications networks.

2 Metamaterials for Antennas

Metamaterials find their mature use in passive antennas. No matter whether to reduce the mutual coupling to improve the isolation between cells, or to change the resonance to alter the phase of the cells, the essence is to adjust the surface impedance of the metamaterial. The following are some typical applications and the principles：

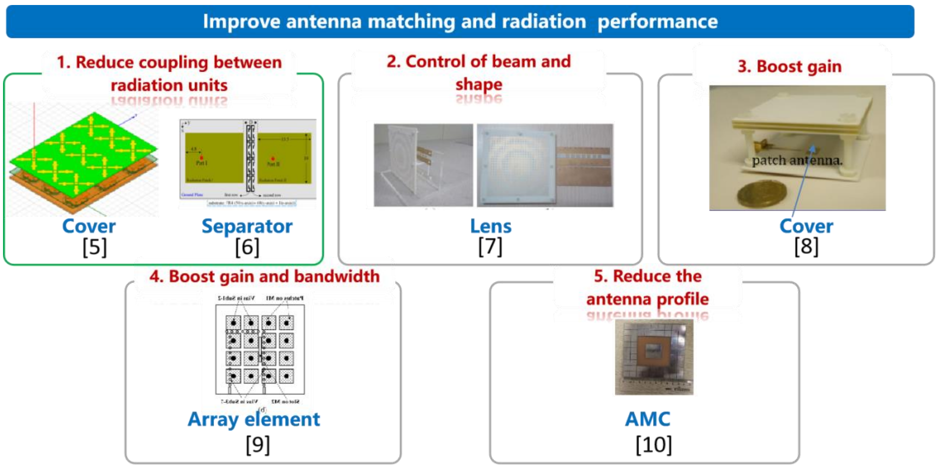

Figure 2. Metamaterials for passive antennas

Metamaterials for antenna covers [5] or metamaterial isolation strips [6] can impede the wave propagation between antenna units, thereby reducing the cross-antenna coupling and improving the isolation between units. Alternatively, the metamaterials can be used as antenna reflectors to achieve "electromagnetic transparency" between antennas of different bands, thus facilitating the multi-band antenna integration in a limited space. This type of application is already seen in some base station antennas.

In addition, planar lenses made up of periodic structures with different phase responses can replace the conventional curve-shaped lenses [7], which simplifies the conformal and manufacturing process, and can form multiple beams by placing different feed sources in the focal plane. Beams can be focused to a shaper direction through the metamaterial cover of ZIM [8], thus enhancing the antenna gain. Periodic or quasi-periodic arrangement of metamaterial arrays, when applied to the radiation unit of antenna arrays [9], can hamper the surface wave propagation, which not only reduces mutual coupling, but also broadens the bandwidth and boost the antenna gain.

AMC metamaterial structure can also lower the antenna profile without sacrificing the antenna gain [10]. The idea is as follows. In traditional antennas, the spacing between radiation unit and the underlying metal reflector plate is often 1/4 wavelength. This is due to the fact that when the metal plate is illuminated by the antenna radiation unit, the phase of the reflected wave would be added 180 degrees. In order to ensure high radiation efficiency, that is, to maintain the in-phase relationship between the reflected wave and the radiated wave by antenna elements, the antenna elements and metal reflector plate should be separated by 1/4 wavelength. If the AMC is used instead of a metal plate, the reflected phase can be zero when the antenna radiation unit illuminates the upper AMC, i.e. the 1/4 wavelength spacing would no longer be needed, thus significantly reduce the height of the antenna.

3 Intelligent reflecting surfaces

Intelligent reflecting surface (IRS), also known as reconfigurable intelligent surface (RIS), is a reconfigurable metasurface. Due to the passive reflection characteristics and simple hardware architecture, RIS brings a new network paradigm of 6G communication systems by constructing a controllable wireless environment to meet the needs of future mobile communications. In the following section, RIS will be discussed from four aspects: technical principles, operation modes, application scenarios, performance verification and challenges

3.1 Principle

In traditional wireless environments, a wireless signal would encounter obstacles in the transmission process. After reflection, refraction and penetration, the multipath components are generated: signals would arrive at receiving ends with different amplitudes, phases and delays. Since these multipath copies would superimpose with the direct-path signal either positively or negatively. multipath fading would occur, which can seriously degrade the performance of wireless system. In contrast, by smart control of a large number of low-cost electromagnetic units on RIS, wireless propagation environment can be reconstructed in a controllable manner, so that uncertain channels become deterministic. As shown in Figure 3, the reflection phase shift of the electromagnetic unit of the RIS is properly tuned so that the reflected signal by the RIS and the signals along other paths can be superimposed constructively at the receiver to enhance the quality of the signal.

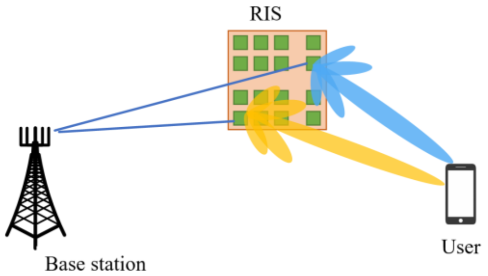

Figure 3. Schematic diagram of the smart reflector

RIS would normally consists of a large-scale device array and a control module. The large-scale device array is featured by the huge number of device units regularly arranged and repeatedly on a planar substrate. In order to fulfill the goal of phase manipulation, hundreds or thousands of device units are usually required for a RIS panel. Each device unit has a device structure that is tunable. For example, the device unit contains a PIN diode where the switching state of the PIN diode determines the response mode of the device unit to the incident wireless signals [11]. A typical hardware architecture is shown in Figure 4 that consists of three layers and a control module. In the outer layer, a large number of metal patches are printed on the dielectric substrate and would directly interact with the incident signal. In the middle layer, copper plates are used to prevent the leakage of signal energy. Finally, the inner layer is a control circuit board responsible for adjusting the amplitude/phase shift of each unit. The inner layer is connected to the RIS array control module [12].

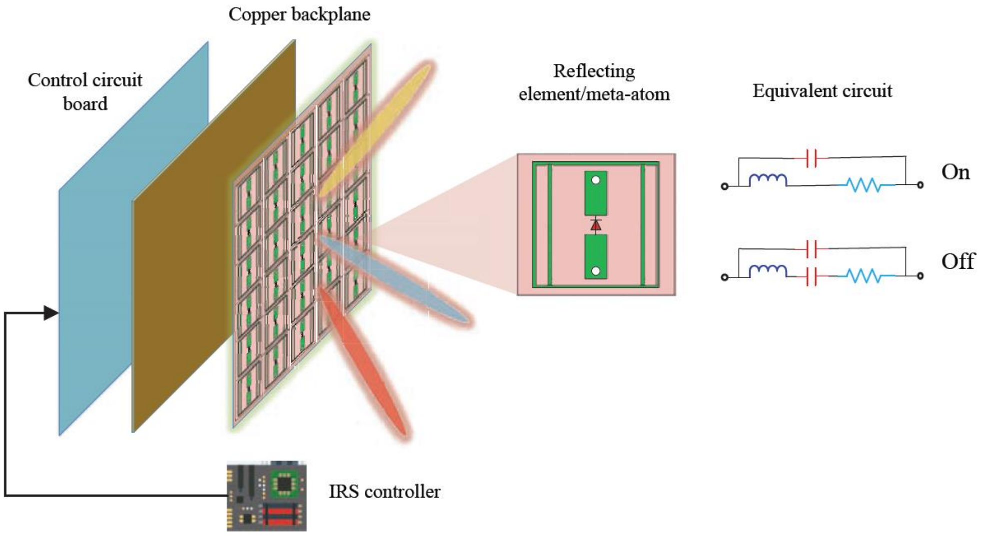

Figure 4. Structure of RIS [12]

The RIS array control module can control the working state of each device unit, that is, to tune the parameters of each unit and adjust the amplitude and phase distribution of electromagnetic waves surrounding the unit, to dynamically or semi-statically control the working state of each unit and achieve different response modes to wireless signals. The wireless response signals of each device unit of the large-scale device array are superimposed, thereby forming desired beams and significantly improving the channel capacity and spectral efficiency of the wireless system.

3.2 Operation modes

Currently, the academic research of RIS is mostly based on idealistic assumptions and focuses on theoretical performance upper bound of RIS-aided communications systems. However, in real deployments, various issues need to be considered such as quantization errors, processing complexity, computing power, system overhead, etc. Therefore, the "three-step" operation mode, from static to dynamic, that gradually approaches the theoretical upper bound, is more in line with the normal migration of stages of a technology. Based on the flexibility of the beam control, the RIS can have three operation modes, as shown in Figure 5, which are static/semi-static operation mode, beam sweeping based dynamic operation mode and channel state information (CSI) based intelligent operation mode.

1. Static/semi-static operation mode

The mode represents the initial stage of RIS technology where the reflector beam can be fixed or have long time intervals for adjustment. This mode of operation is suitable for small areas with poor coverage, or completely blocked where mobile terminals need to rely on the reflecting surface to access the network. This mode has the advantages of simple control and quick deployment. However, since the direction of reflected beam is fixed over long period of time, it is difficult to perform -user-specific beamforming. Nor can it determine the optimal beam responses for channels that are dynamically changing.

2. Dynamic mode with beam sweeping

In this mode, dynamic channel information is not needed for RIS phase adjustment. Instead, the phases of RIS can be adjusted based on multiple beam directions (e.g., codebooks) already known. The user feeds back information corresponding to the optimal beam direction by measuring the channel quality. Then the base station configures the RIS to the selected beam direction. This mode of operation does not require small-scale channel state information, the candidate beam directions are predefined and fixed, leading to the small overhead for control indication. However, multiple rounds of beam adjustments would cause bigger system overhead.

3. Intelligent operation mode with CSI

In this stage, the base station configures the element phases of reflecting surface. Channel estimation is carried out by multiple times of phase adjustment of RIS. The reflecting phases are configured to adapt to the actual channel according to the channel estimation result. This operation mode is expected to deliver the optimal performance. Nevertheless, the channel estimation and the entire procedure are very complicated, adding significant system overhead.

Based on the above analysis, the beam sweeping based dynamic operation mode can be a good trade-off between performance and overhead, and is a key direction of the current research. The basic signal flow of RIS in this operation mode is illustrated in Figure 6.

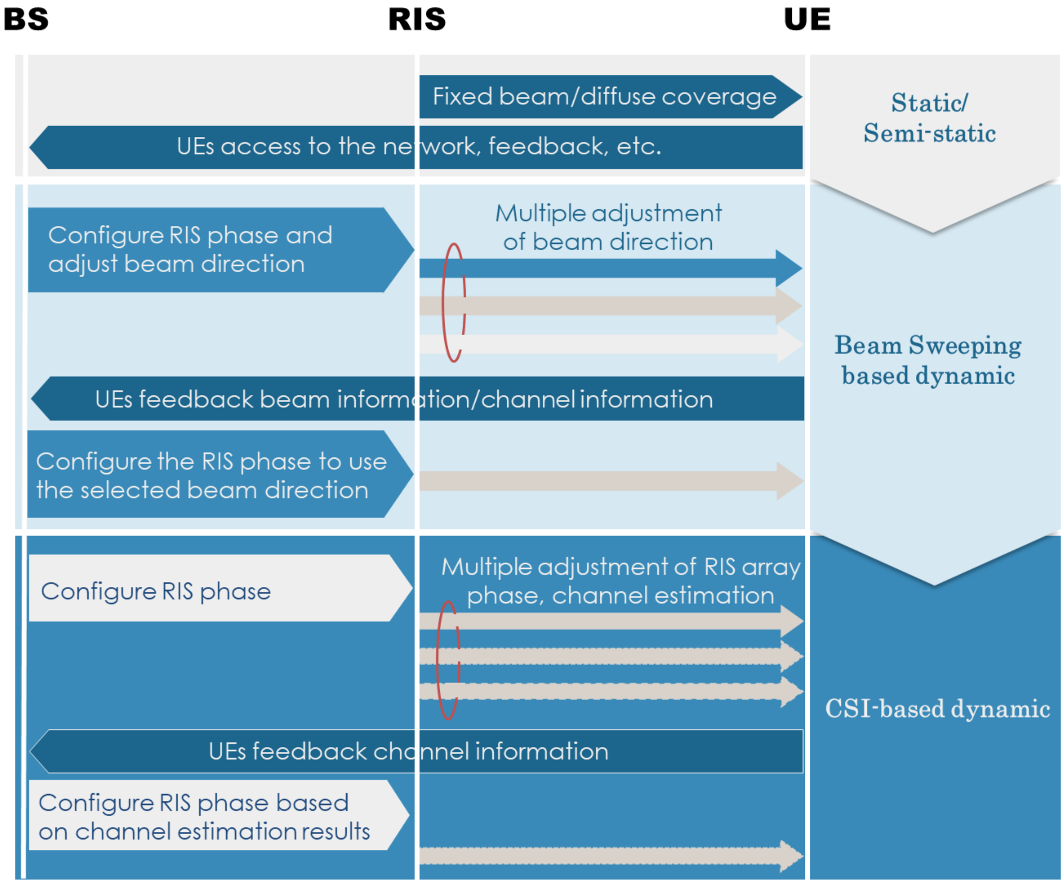

Figure 5. The three working modes of RIS

In order to make RIS flexibly tunable, base station is required to exert control over RIS, which can be through wired connection, IP routing, wireless connection or autonomous sensing. Balancing the deployment flexibility and power consumption, the wireless controls by base station seem more feasible. At this stage, the control signaling ca be based on the Uu interface protocol while also considering the necessary change of protocol flow and signaling due to the introduction of RIS panels to the systems. This would help to accelerate the commercialization of RIS

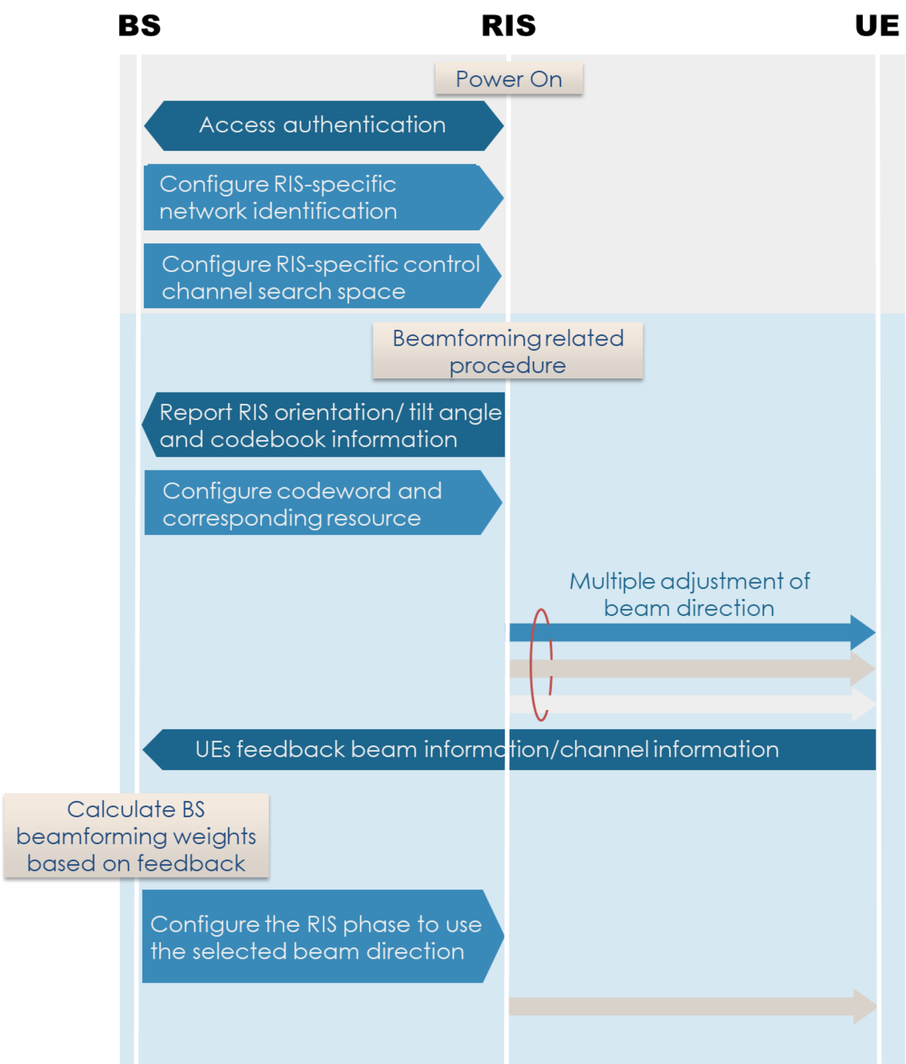

Figure 6. Flow diagram of beam sweeping based dynamic mode

It is known that channel estimation can lead to excessive overhead for RIS with large number of reflection elements. The codebook-based reflection phase adjustment scheme shown in Figure 6 has the following advantages. First, this scheme does not require iterative joint beam optimization between the base station and the RIS. Instead, the base station only needs to assign the proper codeword of RIS element phases based on the selected reflection phase codeword. Second, the codebook-based adjustment does not need channel state information with respect to each RIS element, so that the terminal only needs to estimate the cascaded channel state information (base station to RIS and RIS to terminal), which drastically reduces the complexity of channel estimation. Based on the above analysis, the scheme in Figure 6 can get performance benefit from dynamic phase adjustment while enjoying the low complexity of implementation, which can serve as a reference for subsequent system design.

3.3 Application scenarios

Future mobile communications services require higher data rates, more connection densities, more spectrum resources and more efficient spectrum utilization. On the one hand, RIS can reduce the energy consumption for wireless transmission of the Internet of Things (IoT), and on the other hand, it can increase the channel capacity without using additional spectrum resources. RIS has the advantages of quasi-passive, low power consumption, and flexible deployment. Through the intelligent control of electromagnetic wave propagation characteristics, RIS has great potential to improve the transmission rate, coverage, and energy efficiency of mobile communications systems. The potential application scenarios of RIS can be divided into traditional communications applications and new applications in vertical industries [4], as shown in Figure 7.

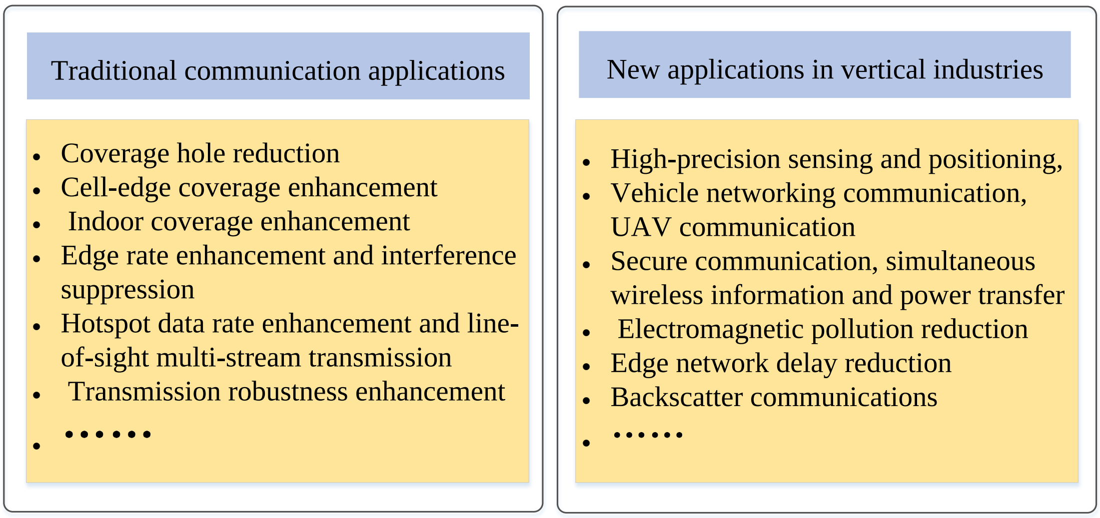

Figure 7. Applications of RIS

1. Traditional communications applications

The applications of RIS in traditional communications include coverage hole reduction, cell-edge coverage enhancement, indoor coverage enhancement, cell-edge rate enhancement and interference suppression, hotspot enhancement and multi-stream transmission for line-of-sight, and transmission robustness enhancement, etc.

2. New applications in vertical industries

Potential new application scenarios of RIS have been discussed in many existing literatures. Typical applications include high-precision sensing and positioning, vehicle-to-X networks, UAV communications, secure communications, simultaneous information transmission and power transfer, electromagnetic pollution reduction, edge network delay reduction, and backscatter communications, etc.

3.4 Performance Testing

To explore the practical performance and application scenarios of RIS, as well as its potential problems in indoor and outdoor deployment, China Mobile completed a field test to validate the feasibility of RIS in a 5G live network environment at Nanjing in June 2021, in collaboration with the team of CUI Tiejun, an academician of CAE, at Southeast University and the Hangzhou Qiantang Information Co., Ltd. In the test, the RIS new technology to be validated has adjustable electromagnetic unit components and is capable of flexible control of the beamforming direction.

1、Testing Environment

To ensure that the test result would truly reflect the effect of RIS at cell edge and in poor coverage areas, the operating frequency was locked for all UEs used in the validation. Furthermore, the validation was conducted in multiple scenarios to cover the actual environments comprehensively, including under-the-tower shadowing, indoor coverage from outdoors, and outdoor traversing.

1) Under-the-tower shadowing

An "under-the-tower shadowing", i.e., a poor coverage zone, often exists under a base station tower, due to the limitations of the down-tilt angle of the base station antenna and antenna direction. A RIS was installed at a location in the test cell with good quality of reception. Parameters of the RIS panel were adjusted so that signals from the base station would be re-directed to the under-the-tower shadow zone. The cumulative density functions (CDF) of several key indicators such as RSRP, SINR, and user throughput, were compared to examine the overall improvement of signal coverage by RIS and validate whether the RIS can support the high-speed services for users in the zone. Figure 8 shows the site of this test case. The selected cell base station is mainly responsible for covering the urban streets. The RIS, installed diagonally opposite to the road in front of a building, received signals from the base station (46 meters above) on the 13th floor of the building and reflected the signals to the poor coverage area at the back of the building. The line-of-sight distance between the base station and the RIS was about 120 meters and the transmission was mainly line-of-sight (LOS).

Figure 8. Image of the Site for the Under-Tower Shadow Zone Test

2）Indoor coverage from outdoors

Electromagnetic signals can be significantly attenuated when penetrating through concrete building walls, glass curtain walls, and aluminum alloy building materials. Therefore, in most cases, indoor environments are typically coverage poor. By properly tuning the shape the reflected beam, the RIS can enhance indoor signal coverage with more focused beams for deeper penetration. In the test case of indoor poor coverage, the overall effect of RIS in the "indoor coverage from outdoors" scenario was examined by comparing the performance difference before and after RIS installation at multiple points. The indoor scenario of the test case was in an office building with glass curtain walls. Stable transmission tests were conducted at multiple points inside the building. The RIS reflection panel was installed on the opposite side of the road under the building. The straight-line distance between the base station and the RIS was about 65 meters and the transmission path is line-of-sight (LOS), as seen in Figure 9.

Figure 9. Image of the Site for the "Indoor Coverage from Outdoors" Test

3）Outdoor traversing

RIS can flexibly control the reflected beam directions and shapes and thus can be used for filling the coverage holes, improving the coverage at cell edges, and etc. The outdoor traversing test was conducted in dense urban area. The effect of the installed RIS on cell coverage was investigated by comparing the performance indicators of UE traversing in the cell before and after the RIS installation. In this test case, a pole-mounted site (10 meters high) in an urban area with a dense population was selected. Due to the blocking by high-rise buildings in the test cell, the signals of the pole-mounted site can only reach a limited range. (The road perpendicular to the one where the pole-mounted site stood was a weak coverage area.) The RIS was deployed at a crossroad 70 meters away from the pole-mounted site and would receive signals from the pole-mounted site and reflect to the weak coverage road in the test cell. UE traversing was conducted over the weak coverage road at a constant mobile speed before and after the RIS deployment respectively. The transmission path between the RIS and the UE, and t between the UE and the base station were primarily LOS. See Figure 10 for the image of the site for this test case.

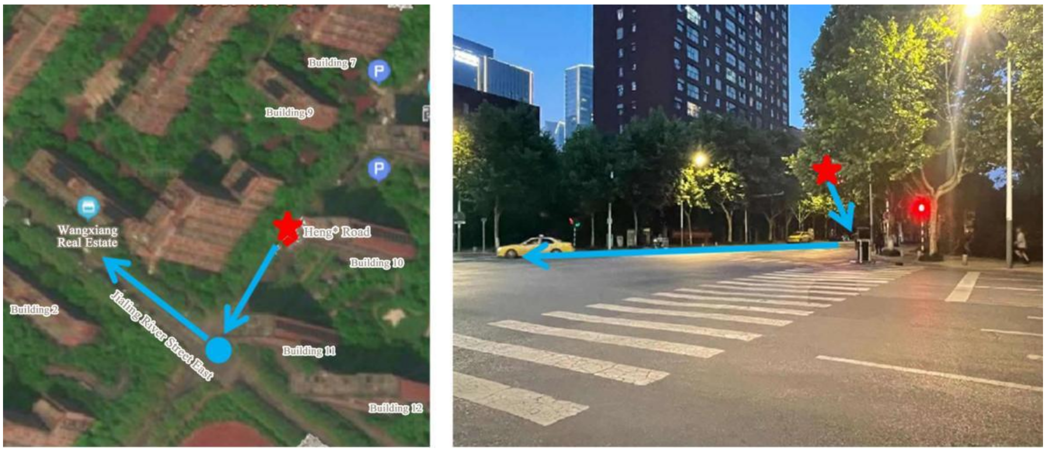

Figure 10. Image of the Site for the Outdoor Traversing Test

2、Base Station and Cell Configuration

Two outdoor base stations were involved in the above test cases. One was on the 13th floor of a high-rise building with glass curtain walls and the other was a pole-mounted site in an urban area with a dense population. See Table 3-1 and Table 3-2 for information about the base stations and cells.

Table 3-1 Base Station Configuration Information

Test Case	Type	Transmission Power	RRU Type	Base Station Model	Downtilt Angle of Installation	Direction Angle of Installation
Under-tower shadow zone	Outdoor base station	327 W	64 channels	Huawei	9°/10°	60°
Indoor coverage from outdoors						
Outdoor traversing	Outdoor base station	327 W	64 channels	Huawei	6°/ 3°	200°

Table 3-2 Cell Configuration Information

Test Case	Sector Number	Downlink Frequency Point	Downlink Bandwidth	Physical Cell Identification	Cell Duplex Mode	Timeslot Ratio
Under-tower shadow zone	1	504990	100	301	TDD	8:2
Indoor coverage from outdoors						
Outdoor traversing	2	504990	100	13	TDD	8:2

3、RIS Panel Configuration

The field performance test was jointly conducted by China Mobile, Southeast University, and Hangzhou Qiantang Information Co., Ltd. using a 160 cm*80 cm panel.

Figure 11. RIS Prototype for Field Test

4、Results and conclusions on the field tests

1）Under-the-tower shadow zone

Respectively before and after RIS deployment, a UE was carried to loop through the under-the-tower shadow zone at a constant speed along the same route. Dot figures of RSRP, SINR, and throughput before and after the RIS deployment are shown in Figure 12.

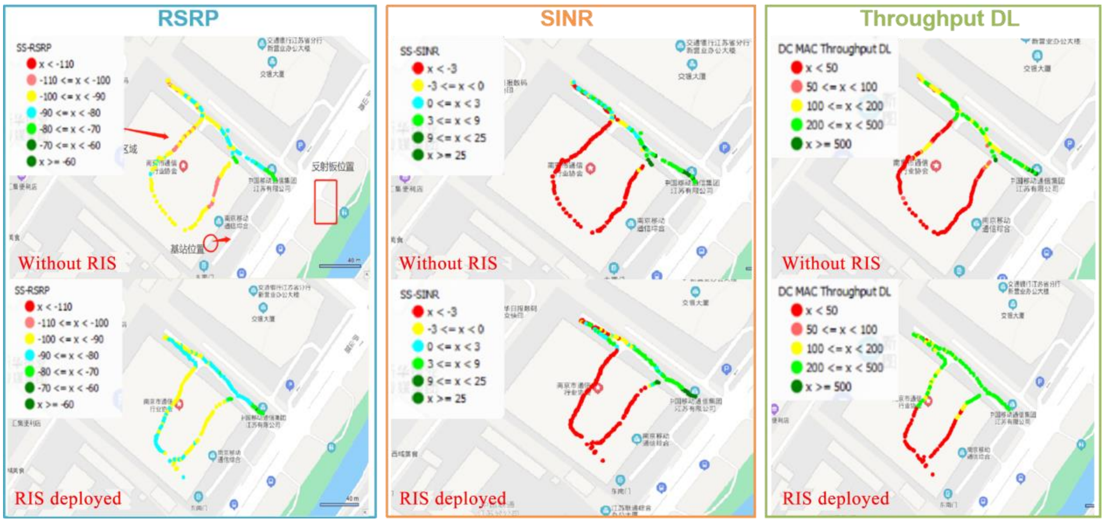

Figure 12. RSRP, SINR, Throughput Dot Figures Before and After RIS Deployment in Under-the-Tower Shadow Zone Test Case

When the RIS is deployed, it is found that the RSRP and throughput improve significantly. and the poor coverage areas shrink considerably. Less improvements were observed in SINR, probably because the RIS also enhanced the interfering signals from adjacent cells Also, more substantial performance improvement was observed at the back of the office building l, although the UE-RIS transmission path was NLOS. A possible reason for this phenomenon could be due to the rich refraction and diffraction caused by nearby obstacles which would be further amplified by the RIS so that the signals received at the UEs in that area would be strong enough.

The test results indicated that before RIS was deployed, both cell edge RSRP and average RSRP of users were rather low, e.g., at -102.18 dBm and -94.93 dBm, respectively. After RIS was deployed, RSRP was increased to some extent. The RSRP gains for cell edge users and average users were roughly 4.03 dB and 3.8 dB, respectively. The average user throughput was increased from 91.50 Mbps to 109.00 Mbps, e.g., up by about 19%.

2）Indoor coverage from outdoors

The indoor scenario was set up on the 2nd and 4th floors of an office building with glass curtain walls. For the office area on the 2nd floor, eight points were selected, covering three typical scenarios: conference room, office, and studio. The 4th floor was a supermarket, where stable transmission tests were conducted at four locations. Figure 13 shows a diagram of the test point locations.

Figure 13. Schematic Plan for Fixed-Point Transmission Test in the Office Building

It was found during the test process that the UE could not receive the downlink signals from the base station when it was behind the indoor reinforced concrete walls. This suggested that the RIS panel used in the test would have limited penetration capability to cover indoor environments from outdoors: it would not be able to further penetrate an interior wall after going through the external glass curtain wall. The following data were obtained by averaging the data recorded over one minute of stable signal transmission at each point as long as the downlink signals were detectable.

Preliminary conclusions can be drawn by analyzing of the fixed-point transmissions t. Specifically, after RIS was deployed, RSRP, SINR, and transmission rate were improved at most location points. Despite the penetration loss of the glass curtain wall, 3~17 dB gains in RSRP were still observed, roughly 10 dB on average across all measured locations, and the transmission rate increases range over 5~137 Mbps, with averaging gain of 78.19 Mbps across all locations. The performance improvements varied significantly across different locations, probably due to signal fluctuations and limited range of RIS coverage. Although the overall gain was substantial, the signals failed to overcome the interior wall (an extra 15 dB penetration loss) as the indoor coverage where the basic signal level was quite low (about -100 dB). In addition, the gain was not significantly improved in the right-most area on the 2nd floor which was not covered by the RIS reflected beams due to the limited beamwidth RIS.

3）Outdoor traversing

The outdoor traversing test was conducted by carrying a UE to loop through the test cell at a constant speed along the same route, before and after RIS deployment. This resulted in the RSRP, SINR, and throughput dot figures shown in Figure 14.

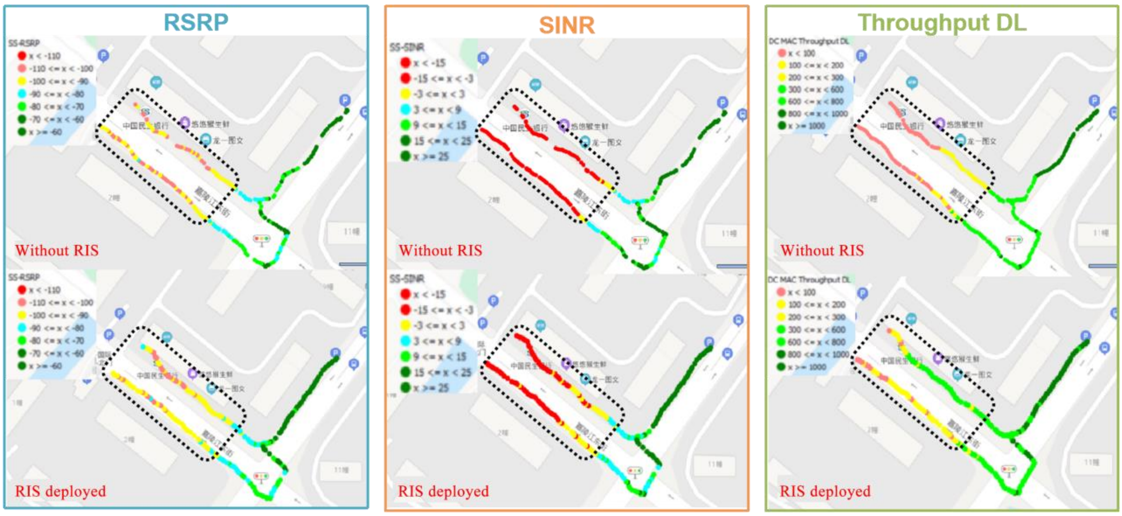

Figure 14. RSRP, SINR, Throughput Dot Figures in the Outdoor Traversing Test

The dot figures show that RIS deployment did not cause significant performance changes n areas where RSRP was greater than -80 dBm. However, in areas where RSRP was lower than -90 dBm, RSRP, SINR, and throughput became significantly better after the RIS was deployed.

Further, the test results show the significant impact of RIS deployment on cell edge performance, e.g., RSRP, SINR, and throughput increased by about 3.3 dB, 1.45 dB, and 79 Mbps, respectively. In contrast, the average RSRP for all users was improved by merely 1.25dB. In addition, to examine the effect of RIS on the cell coverage, a test of isolate base station was conducted where the UE moved kept away from the base station until the connection was dropped. Before the RIS was deployed, the maximum distance was 150 meters. After the deployment of RIS, the maximum distance was increased by about 60 meters, e.g., 210 meters. This test case demonstrated the significant practical value in improving p cell edge users' performance and extend cell coverage.

The test results can provide a preliminary understanding of the suitable scenarios of RIS and the potential performance gains. For low frequency bands, poor coverage areas are not common. Therefore, RIS can be used to improve spectral efficiency and system capacity; for high frequency bands, more coverage holes are expected. Hence, RIS can play an important role in improving coverage and capacity.

4 Beamforming metasurface base station

Metasurface-based beamforming base station system is one of the hot research areas of RIS in recent years. In such system, beamforming can be achieved via intelligent control of the reflection or transmission characteristics of a large number of low-cost electromagnetic units. In the actual system, the digital coding of metasurface can be designed by including the array coding optimization algorithm to change the amplitude and phase of electromagnetic wave for each unit. Thus, the gain and the pattern of radiated beams can be controlled. The combination of the beamforming-capable metasurface and the traditional digital baseband technologies would spawn an entirely new base station architecture. In the future, the parameters of metasurface-based beamformer at the base station and the reconfigurable intelligent metasurface relay can be jointly designed to improve the transmission rate, coverage, and energy efficiency of the mobile communication systems, and further reduce the cost and power consumption.

4.1 Principle

The beamforming design mainly includes the design of precoding and decoding matrix for multi antenna transceiver to achieve directional transmissions. In the metasurface-based beamforming for base station, the metasurface is equivalent to a low-cost phased array antenna with multi-bit phase shifter function. A prototype schematic diagram and the comparison with the traditional base station are shown in Figure 12. Compared with the traditional base station, metasurface-based beamforming base station replaces the phase shifter and antenna array, and thus reducing the number of RF channels and power amplifiers. In metasurface-based architecture, a large number of tunable units, each with size of sub-wavelength, are introduced where the tunable components are mainly switching diodes or varactor diodes. By controlling a large number of programable elements on the metasurface, spatial phases can be fine-tuned, that is, phases of elements at different positions can be controlled. Different phase distributions result in different incident, reflection and transmission characteristics of electromagnetic wave, so that, the beamforming function can be achieved with lower cost and power consumption compared to the traditional phased arrays.

It is the programmable characteristics of metasurface-based base station that allow external analog precoding for the corresponding phase matrix. In order to form beam in a specific direction, an equal-phase surface needs to be generated in this direction when the radiation fields of tmetasurface units are superimposed. Based on the desired antenna pattern, coding sequence can be calculated by reverse synthesis. The metasurface-based base station beamformer can use the coding sequence to optimize the reflected or transmitted beams, so as to reduce the required transmission power, to improve the spectral efficiency, expand the coverage and suppress the interference at the same time.

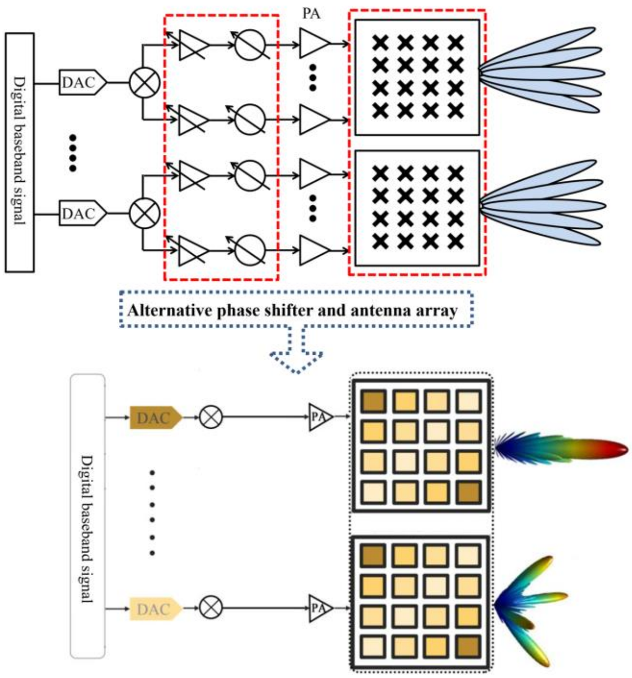

Figure15 Comparison between metasurface-based base station beamforming and traditional base station

4.2 Challenges

The metasurface-based base station beamforming can meet the performance requirements while effectively reducing the cost by using low bit control unit. However, low bit control unit would increase the grid lobes in large angles, thus deteriorating the performance of other users in multi-user transmissions. Put in the networks, grid lobes would interfere with other cells and even other operators' networks. Therefore, it would be problematic if low bit metasurface-based base stations for beamforming are deployed in multi-user, hot spot scenarios.

Secondly, a metasurface panel typically consists of thousands of units. Partial failure of some control elements may prevent metasurface units from achieving the expected performance target. Also it would be difficult to troubleshoot and repair failed units. When the number of faulty units increases, the performance of the entire metasurface panel will be significantly reduced, such as the loss of beamforming gain, the deviation of beam direction, the increased sidelobes and so on.

5 Direct modulation metasurface base station

5.1 Principle

It is a new base station architecture that relies on intelligent metasurfaces to directly modulate the phase, amplitude, frequency and polarization without complex baseband processing and RF transceiver operations1]. The principle of the metasurface-based transmitter is illustrated in Figure 16, where a single-tone signal from the feed source is irradiated onto an intelligent metasurface, and the digital baseband signal is used to real-time control the amplitude, phase, frequency and polarization of the reflected/transmitted electromagnetic wave without circuit-level modulation, mixing and antenna radiation. This eliminates the need for circuit-level modulation, mixing and antenna radiation, and would ultimately allow intelligent metasurfaces to directly modulate and transmit baseband signals.

Compared with conventional transmitters, information modulated metasurface transmitters can replace the analogue devices in the RF chain of conventional transmitters as shown in Figure 16. Since the frequency modulation and filtering are carried out on the metasurface without the need for mixers and RF filters, only narrow-band power amplifiers are required to boost the power of the air-fed single-tone carrier signal, thus partially replacing the analogue devices such as mixers, filters, power amplifiers and other parts of the conventional RF chain, thus reducing the complexity of the overall structure and design and manufacturing costs, achieving the reduced power consumption and improving the energy efficiency.

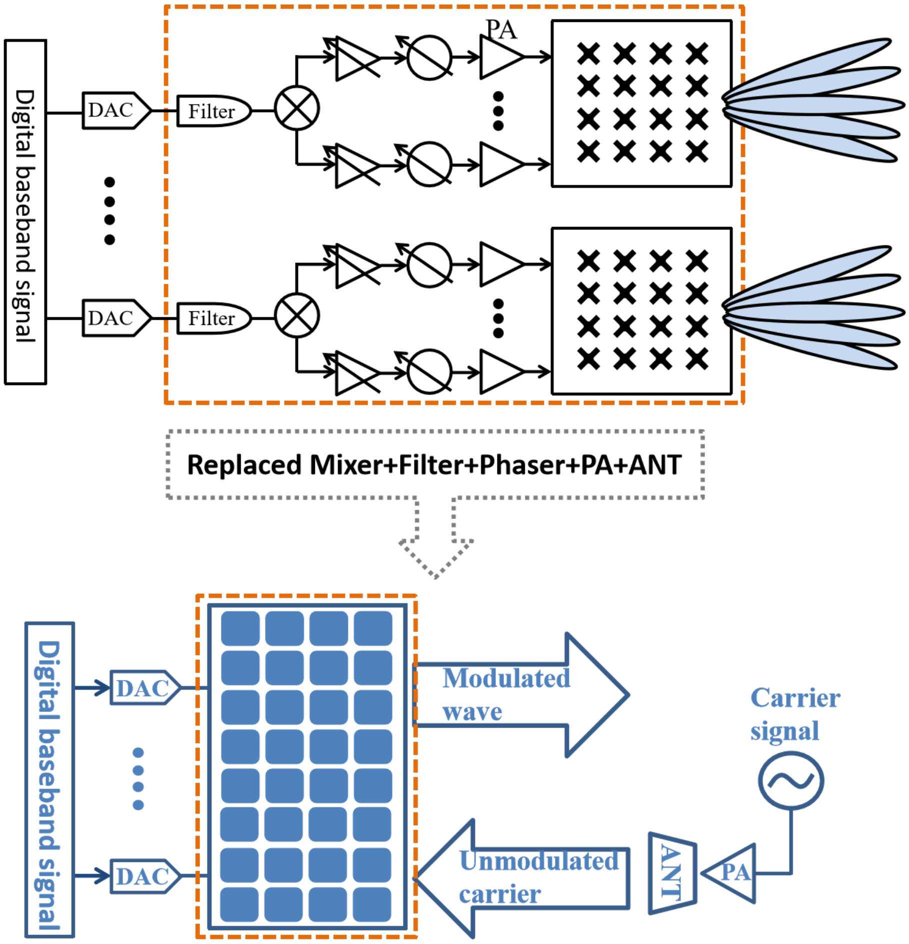

Figure 16. Comparison of information modulated metasurface transmitters and conventional base stations

5.2 Challenges

Various information modulated metasurface communication systems have been proposed, including binary frequency shift keying (BFSK), quadrature phase shift keying (QPSK), higher order modulation schemes (e.g. 8PSK, 16QAM, OFDM, etc.) and space domain modulation based on space-time coding (STC) for time division, frequency division and space division multiplexing regimes, all of which have demonstrated their performance potential. However, from a practical deployment point of view, there are still many problems to be solved for information modulated metasurface base stations.

Firstly, the tunable devices used in the current intelligent metasurfaces are mainly switching diodes or varactor diodes. In order to enhance the electromagnetic tunability of the metasurface, it is often necessary to configure multiple switching diodes in each unit and to carry out complicated design for metasurface devices, adding design difficulties and manufacturing costs.

Secondly, regardless whether to use switching diodes or varactor diodes, the current response rate is not fast enough to meet the requirement of future wireless networks for wide bandwidth and high-speed transmission. Currently, the fastest response rates are in the nanoseconds for switching diodes and microseconds for varactor diodes, while both can only support transmission bandwidths in the MHz range. Therefore, to support wide bandwidth, the response time of tunable devices should be in picoseconds. However, there is still a bottleneck for diodes. Considering the materials to build diodes, Si-based diodes have difficulties in high frequency band operation. They also have the issue of high energy loss, GaAs semiconductor may be a solution.

In addition, the existing information modulated metasurface base stations only have a transmitter side architecture, the receiver architecture has not yet been proposed and is subject to further research.

6 Summary

This white paper presents China Mobile 's initial thinking on the applications of information metamaterials in 6G. The while paper will be updated according to the research progress. China Mobile will continue to collaborate with universities and industries to increase the investment in information metamaterials research, build a innovation platform for industry, universities and research, and jointly push the development of information metamaterials for their successful deployment in 6G communications systems.

7 Contributors

In the white paper, China Mobile Research Institute is mainly responsible for Chapters 2, 3, 4, and Chapters 5 and 6, and the Institute of Electromagnetic Space of Southeast University is responsible for Chapters 1 and 3. The main contributors to the white paper are as follows:

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