RECENT ADVANCES OF ULTRAMASSIVE MULTIPLE-INPUT, MULTIPLE-OUTPUT TECHNOLOGIES

Realizing a Sixth-Generation Future in Spatial and Beam Domains

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To explore the full potential of ultramassive multiple-input, multiple-output (MIMO) communication systems, it is fundamental to understand new ultramassive MIMO channel characteristics and establish pervasive channel models. On this basis, large-dimensional spatial-temporal transmission and random access technologies need to be investigated and evaluated for better practical implementation. First, this article reviews recent advances of ultramassive MIMO technologies in the traditional spatial domain, including wireless channel characterization and modeling, channel estimation, spatial multiplexing, and precoding. Second, considering the dramatic increase of base station (BS) antennas and access users in ultramassive MIMO systems, the confronted high-dimensional complexity and computing burden of these ultramassive MIMO technologies are indicated. To provide an efficient and systematic solution, the emerging tendency to transform related technologies from the traditional spatial domain to the beam domain is introduced. The utilities of large sparsity merit, reduced energy consumption, and improved usage of radio frequency (RF) chains in the beam domain channel are elaborated. Last, future challenges of ultramassive MIMO communication systems are discussed.

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Introduction

To realize the visions of the 6G wireless communication system, full utilization of spatial, temporal, frequency, and code resources have been explored to serve ultramassive transmission and access of users/devices and to provide high-quality communication even in very high-mobility scenarios [1], [2]. Ultramassive MIMO, evolving from long term evolution (LTE) MIMO and massive MIMO, equips hundreds or thousands of antenna elements at the BS can serve tens or hundreds of users with the same time and frequency resources simultaneously. Benefiting from the abundant spatial degrees of freedom, the ultramassive MIMO technology is a perfect candidate catering to 6G demands. It can greatly increase channel capacity, energy efficiency, and spectrum efficiency. However, it also poses challenges to hardware design, signal and arithmetic design and processing, resource allocations, etc.

The design of the ultramassive MIMO system is highly reliant on fundamental physical layer (PHY) theories and technologies. As shown in Figure 1, wireless channel measurements, multipath component (MPC) parameter estimation, channel characteristics analysis, and channel modeling are essential procedures to understand the statistical properties of the ultramassive MIMO channel. They are useful to clarify the dependency relationships of channel statistical properties with array configurations, frequency bands, and other system setups. A pervasive channel model is also an important prerequisite for the following PHY technology design and evaluation. Based on the channel characteristics and channel model, large-dimensional spatial-temporal transmission techniques and random access techniques can be studied, including channel estimation, spatial multiplexing, precoding, etc. [3]. In addition, the impacts of system configurations on energy efficiency, spectrum efficiency, economic/hardware efficiency, sum-rate capacity, and terminal capacity can be analyzed with the aid of massive information theory.

However, with the ultramassive expansion of array size, traditional methods and techniques in MIMO and even massive MIMO systems are no longer suitable for the ultramassive MIMO system. It has already been verified that wireless channels facilitating ultramassive arrays show different propagation characteristics, including more obvious spherical wavefront, spatial nonstationarity, channel hardening, etc. Consequently, traditional MPC parameter estimation algorithms and channel models under plane wavefront and spatial stationary assumptions are not suitable for the ultramassive MIMO channel. In addition, as the large amount of antenna elements require paramount RF chains, this poses a heavy burden on practical implementation as well as channel state information (CSI) acquisition. Due to the imperfect channel estimation under massive pilot overhead, the upper bound of massive spatial-temporal transmission sum-rate and the tradeoff among energy, spectrum, and economic efficiencies need to be studied. Large-dimensional spatial-temporal transmission and random access techniques need to be explored to adapt to more complex communication scenarios. It is also necessary to work on large-dimensional computing theory to support reliable communication in real time. Then, how to reduce complexity with ensured accuracy at each key procedure is crucial for the ultramassive MIMO system.

Traditionally, it is natural to study wireless channel and PHY techniques in the spatial domain. Recently, more efforts have been devoted to research in the beam domain. The beam domain channel can be transformed from the traditional spatial domain channel using unitary discrete Fourier transformation (DFT) matrices. The wireless channel can be observed through transmitter (Tx) and receiver (Rx) beam pairs. The channel coefficient of each beam pair is only contributed by MPCs

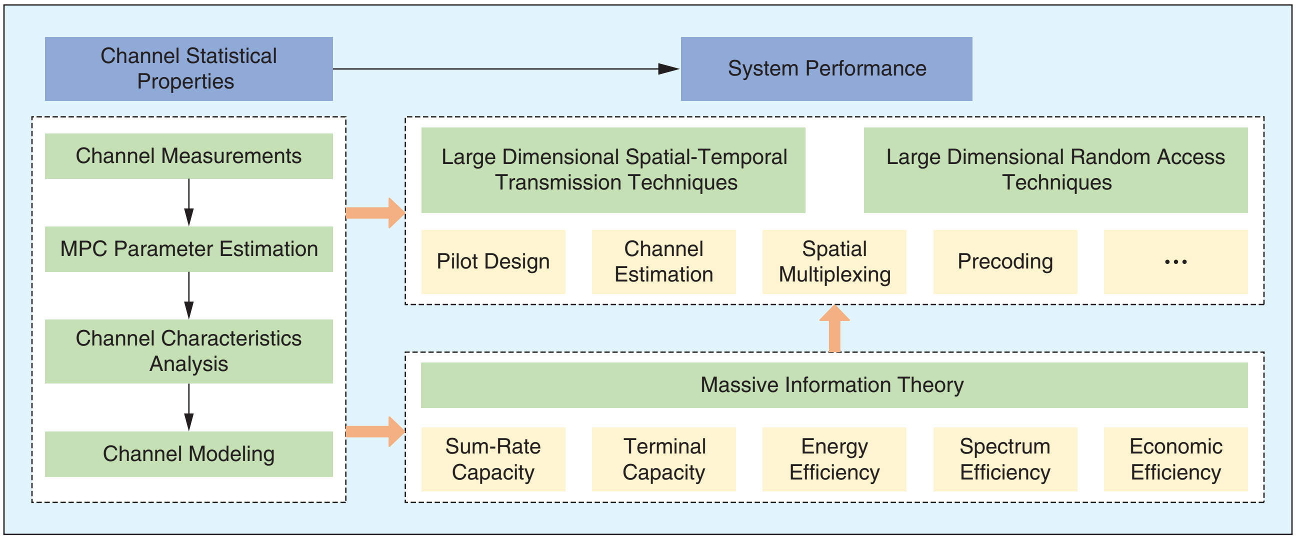

FIGURE 1 Key PHY technologies of ultramassive MIMO. MPC: multipath component.

that fall into this beam pair, i.e., with limited angles of arrival and departure. Considering the clustering nature of MPCs in ultramassive MIMO channels, only a few channel coefficients are related to MPCs, while others are dominated by noise. This is also known as the channel sparsity. It is found that the different beam domain channel elements are asymptotically uncorrelated, and their envelopes tend to be independent of time and frequency [4]. To explore the full potential of ultramassive MIMO communication systems, it is meaningful to fully review the recent advances of ultramassive MIMO channel characterization and modeling, as well as large-dimensional spatial-temporal transmission and random access techniques in both spatial and beam domains.

The remainder of this article is organized as follows. In the "Ultramassive MIMO Channel Characterization and Modeling" section, we focus on the ultramassive MIMO channel characterization and modeling. In the "Ultramassive MIMO PHY Technologies" section, ultramassive MIMO PHY technologies are surveyed in both spatial and beam domains. In the "Future Research Challenges" section, future research challenges are given. Finally, we present the "Conclusions" section.

Ultramassive MIMO Channel Characterization and Modeling

Channel Characterization and Modeling in the Spatial Domain

The comprehensive understanding of ultramassive MIMO channel characteristics and acquisition of wireless channel mathematical expression are meaningful for the design of devices, antennas, radio and signal processing elements, protocols, and systems/networks according to system requirements. It is fundamental to evaluate link-level, system-level, and network-level performance in a realistic, repeatable, and reproducible manner [5].

The channel characterization and modeling rely on carrying out extensive channel measurements, high-resolution parameter estimation, and channel characteristics analysis. Especially for MPC parameter estimation, besides the Bartlett beamforming, Capon's beamformer, multiple signal classification (MUSIC) algorithm, unitary estimating signal parameter via rotational invariance technique (ESPRIT), etc., the commonly used algorithm is the space-alternating generalized expectation-maximization (SAGE) algorithm. However, with the expansion of antenna elements and high temporal resolution brought by millimeter wave (mmWave) and terahertz (THz) bands, the data size and number of parameters to be estimated increase exponentially. This poses a huge challenge to real-time data processing, especially in a high-mobility time-variant scenario. In addition, some new ultramassive MIMO channel characteristics need to be considered. For example, the Rayleigh distance calculated under the ultramassive array becomes large, and the cluster/Rx lying within the Rayleigh distance suffers from the near-field effect. That means that the impinging wave exhibits a spherical wavefront and arrives at the ultramassive antenna elements with different angles and delays. Besides, different antenna elements may see different clusters, i.e., there is spatial nonstationarity along the ultramassive array [2]. While most existing channel parameter estimation algorithms assume narrowband, plane wavefront, and spatial stationary propagation, research on algorithms that consider new massive MIMO channel characteristics needs to be considered.

Wireless channel models can be divided into traditional nonpredictive and artificial intelligence (AI)-based predictive categories [6]. The former category includes the deterministic model, the correlation-based stochastic model (CBSM), and the geometry-based stochastic model (GBSM). The deterministic model and the CBSM perform less satisfactorily in complexity and accuracy, respectively. The GBSM is widely used to provide more flexible and accurate channel modeling. It has already been used to describe new channel characteristics of (ultra-)massive MIMO channels. For example, the near-field spherical wavefront and spatial nonstationarity have been modeled by deriving the MPC travel distance with angle of arrival/angle of departure (AoA/AoD) and visible region/cluster birth–death process, respectively [5]. Likewise, with the increase of antenna elements, the complexity of GBSM becomes not affordable. Benefiting from the nonlinear big data processing advantages, the latter AI-based predictive methods can not only be used to generalize channel characteristic parameters but also to predict channel characteristics at unknown frequency bands and future times. The used algorithms include multilayer perceptron neural network (NN), convolutional NN (CNN), recurrent NN, long short-term memory, random forest, etc. However, the accuracy of AI-based predictive methods is still worth further investigation.

Channel Characterization and Modeling in the Beam Domain

As shown in Figure 2, the beam domain channel is formed by dividing the whole space into several virtual sections according to the three-dimensional (3D) angles. The corresponding cluster is virtual, which contributes to the transmission of signals from one given direction to another. The beam domain channel can also be transformed from the traditional spatial domain by using two unitary DFT matrices.

There is some research that performs AoA estimation in the beam domain. The proposed algorithms mainly include beam domain MUSIC, ESPRIT, unitary ESPRIT, SAGE algorithm, etc. They formulate the beam domain signal model by multiplying the DFT matrices to that in the spatial domain. Especially in massive MIMO channels, the necessary high-dimensional matrix operations can be alleviated to magnitudes of beam number, rather than antenna number. Therefore, the complexity of the channel parameter estimation can be greatly reduced. It can further reduce the computational complexity by considering the limited angular spread and confining the beams to interested sectors. In [7], a beam domain unitary ESPRIT algorithm was introduced by using the DFT matrix to transform the data into a real-valued beam domain. It indicated the benefits of beam domain channel parameter estimation: reduced computational complexity, less sensitivity to antenna array imperfection, and lower signal-to-noise ratio (SNR) resolution threshold. The utilization of beam domain parameter estimation is of more value in ultramassive MIMO since the antenna number is quite large. However, the existing literature lacks multidimensional parameter estimation and needs to be extended for ultramassive MIMO channels.

For the convenience of beam domain channel modeling, ultramassive MIMO channel characteristics in the beam domain need to be studied. To explore the differences of channel characteristics in the beam domain with those in traditional array domain, we have conducted ultramassive array channel measurements and data analysis. The Rx with 128 elements in uniform linear array (ULA) is elevated to the outside wall of a building with 20 m height, and the Tx equipped with eight antennas is positioned on a truck with 1.5 m height. The carrier frequency is 5.3 GHz, and the bandwidth is 160 MHz. As shown in Figure 3, by employing a sliding window with size 20 and step 1, the virtual beam powers at different subarrays are illustrated in a contour map. It can be seen that the dominant MPCs fall within beams 12–18. The powers of these beams are not shifted regularly to other adjacent beams. Therefore, near-field spherical wavefront is not significant in the beam domain. However, other new beam domain channel characteristics need to be studied based on extensive channel measurements and data processing.

The beam domain channel model (BDCM) originated from the virtual channel representation (VCR), which was proposed in 2000 by Sayeed [8]. BDCM characterizes MIMO channels by partitioning the propagation channels into virtual beam spaces. Recently, this model has been developed for massive MIMO channels. In this work, we unify the definition of BDCM and VCR as BDCM. A usual way to establish BDCM of massive MIMO channel is to first set up a GBSM and then transform it into the beam domain by using two unitary matrices. However, when considering spherical wavefront or spatial nonstationarity, it is not easy to derive the corresponding unitary matrices. Another way is to sum MPC contributions into certain beams and to analyze beam domain signal propagation mechanisms, namely, to establish the BDCM directively based on beam domain channel characteristics. Preliminary work on this method can be found in the literature, although new ultramassive MIMO channel characteristics have not been considered. In Figure 4, the channel capacities of the Kronecker-based stochastic model (KBSM), Weichselberger model, and BDCM are compared with that of the channel measurement data. Three Rx array sizes are employed, i.e., 8, 32, and 64. Note that the BDCM is transformed from a 3D massive MIMO GBSM through Fourier matrices. It can be seen that the BDCM performs better than the Weichselberger model and KBSM, especially when the Rx array size increases. This is because with the increased antenna number, the virtual beams of the BDCM become very narrow, and the BDCM performs approximately with the GBSM. It needs to be noted that here we have not taken the new ultramassive MIMO characteristics into consideration, which can further improve the BDCM performance.

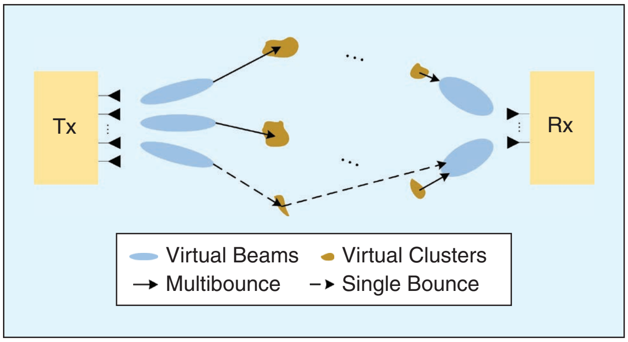

FIGURE 2 Wireless channel in the beam domain.

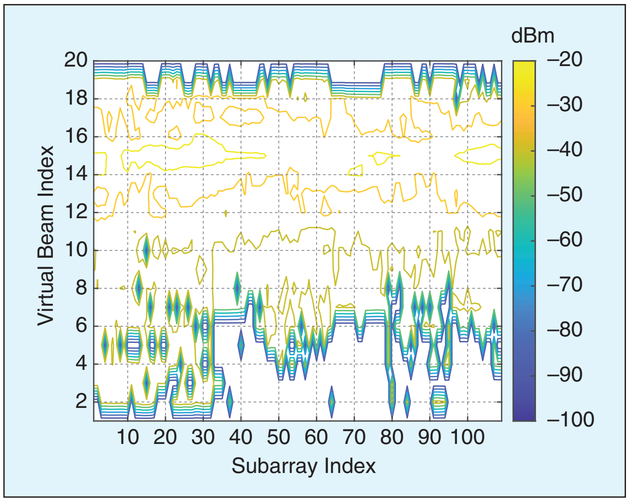

FIGURE 3 Power variations of different virtual beams.

Ultramassive MIMO PHY Technologies

In Figure 5, we illustrate the working flowchart of the ultramassive MIMO system. After careful signal design, signals are first modulated and precoded according to the estimated CSI. With the inserted cyclic prefix, the signals are then transmitted into the wireless channel and received by antenna elements. Then, the cyclic prefix is removed, and equalization can be performed before demodulation and reception. As techniques related to wireless signals and channels can be performed in both spatial and beam domains, in the following, we will focus on giving a review of channel estimation, spatial multiplexing, and precoding techniques.

Channel Estimation

Channel Estimation in the Spatial Domain

Perfect CSI is crucial for the BS to steer beams to desired directions. With perfect CSI estimation, the transmission power efficiency can be proportional to the BS antenna number, and vice versa for the downlink. To obtain the CSI under time division duplex, the BS needs to send pilot signals to the Rx, and the Rx performs channel estimation and sends feedback. The uncorrelated interference and pilot contamination are main factors that can impact CSI estimation performance. Accurate channel acquisition relies on efficient channel estimation algorithms. There are blind estimation and semiblind estimation. The former requires the signal covariance matrix rather than the dedicated pilot signal. The minimum mean square error (MMSE) algorithm can be used to provide power efficiency that is proportional to the square root of the BS antenna number. Channel estimation can also be operated based on the estimated AoA. This method avoids pilot contamination and thus improves spectrum efficiency. However, this method needs extra array calibration and AoA estimation. Considering that the acquisition of instantaneous CSI is a huge task, statistical CSI can be considered instead when the second-order statistics of CSI vary slowly.

However, the utilization of excess antennas at BSs of ultramassive MIMO communications brings overwhelming pilot overhead and computational complexity, even for statistical CSI [9]. The high-dimensional signals and parameters to be estimated hinder the boosting of transmission efficiency. Researchers also resort to AI algorithms to provide accurate estimation with limited samples. Specifically, in fast-moving environments, e.g., vehicle-to-vehicle, high-speed train, and unmanned aerial vehicle, wireless channels change frequently, and coherence times are very small. To provide accurate CSI for the BS, frequent channel estimation needs to be performed. However, the pilot overhead is overwhelming, and the complexity is magnified, especially with the increased antenna number in the ultramassive MIMO channel. To tackle this problem, the sparsity of the ultramassive MIMO channel and the lower variant nature of AoA/AoD compared with path gains can be utilized to estimate the time-varying channel. There are also compressive sensing and machine learning-based algorithms that can be used for time-varying ultramassive channel estimation, e.g., message passing and Gaussian-mixture Bayesian learning. Channel estimation under frequency division duplex also needs to be investigated.

Channel Estimation in the Beam Domain

Utilizing ultramassive MIMO is challenging in terms of the unaffordable hardware complexity and energy consumption. There are many works that employ the lens array to transform the conventional antenna domain channel into the beam domain. Thus, the number of RF chains can be reduced. Resorting to the sparsity of the ultramassive MIMO channel, especially dominant in mmWave and THz bands, it was introduced in [10] that the sparsity of virtual beams can be used to detect pilot contamination attacks

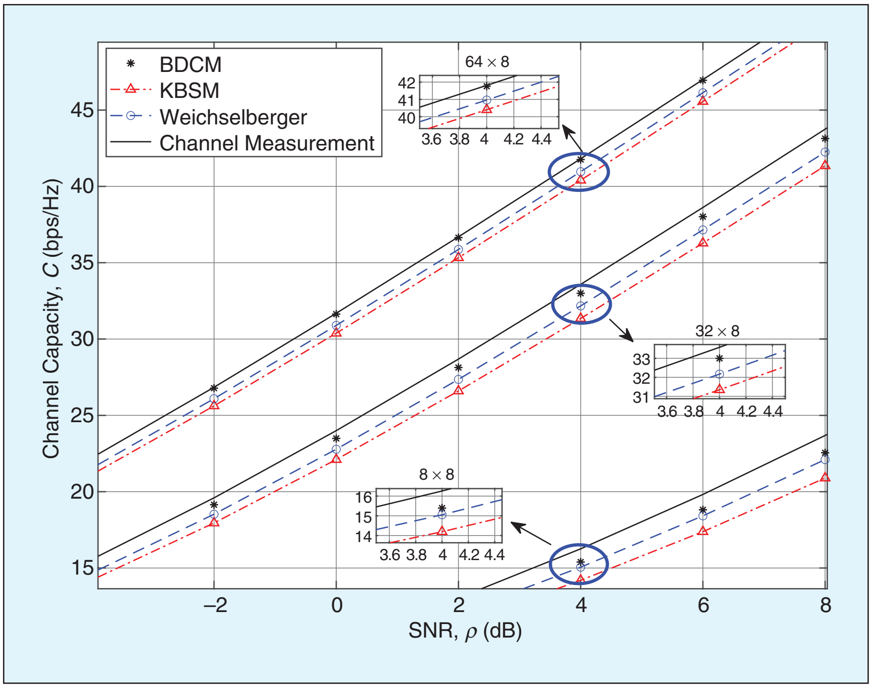

FIGURE 4 Channel capacities of various channel models. KBSM: Kronecker-based stochastic model.

and improve channel estimation results. The beam domain channel estimation can also alleviate the constraints on RF chains.

However, considering the large lens antenna array and reduced RF chains, channel estimation confronts extreme challenges. The compressive sensing method has been used to estimate the channel by utilizing the channel sparsity in the beam domain. For example, orthogonal matching pursuit and compressive sampling matching pursuit algorithms have been used in digital beamforming, hybrid beamforming, etc. In [11], a support beam detection-based beam domain channel estimation scheme was proposed. It considered the sparse virtual beam channels individually. Through the support beam detection, different pilot overheads can be assigned for different virtual beam channels. Therefore, superior performance can be obtained especially in low-SNR conditions. To utilize the sparsity and MPC clustering natures of ultramassive MIMO channels, algorithms for image reconstruction have also been introduced. Further, there are also AI-based beam domain channel estimation methods for the massive MIMO channel to provide better accuracy. For example, there are the approximate message passing (AMP)-based method, Gaussian mixture learned AMP method, and denoising CNN.

Multiplexing

Multiplexing in the Spatial Domain

In MIMO systems, channel capacity and spectrum efficiency can be ensured by the spatial multiplexing technique [12]. By grouping the outgoing signal into multiple streams, multiplexing gain can be obtained by transmitting multiple data streams over paralleled subchannels. At the Rx side, the antenna number needs to be no less than the multiple data stream number; thus, signals can be correctly decoded, and channel capacity can be improved. The high-rate spatial multiplexing is also beneficial for the following spatial modulation and beamforming.

In ultramassive MIMO systems, unprecedented spatial multiplexing capabilities are expected considering the high spatial resolution and favorable propagation conditions. However, the numbers of RF chains at Tx and Rx are usually limited due to hardware complexity. Then, the multiplexing gain is restricted by the smaller number of RF chains. In addition, spatial multiplexing relies on the independence among array elements or subchannels; it handles uncontrolled MPC signals. Whereas with limited scattering, the ultramassive MIMO channels are highly correlated, and MPC channel matrices are low rank. To boost the multiplexing gain, new mechanisms that are tailored for ultramassive MIMO channels need to be considered.

Multiplexing in the Beam Domain

Beam domain multiplexing can leverage the benefits of beamforming and multiplexing, thus obtaining improved array gain and multiplexing gain. In [12], it was indicated that beam domain signal processing, especially the beam domain multiplexing, will play a vital role in future wireless communication systems. It was said that beam domain multiplexing can be used to improve channel capacity and provide better coverage for cell-edge users. The authors proposed a beam domain multiplexing technique and compared that with the spatial domain multiplexing in detail. It was shown that beam domain multiplexing relies on the independence among multiple virtual beams and the correlation of the single beam.

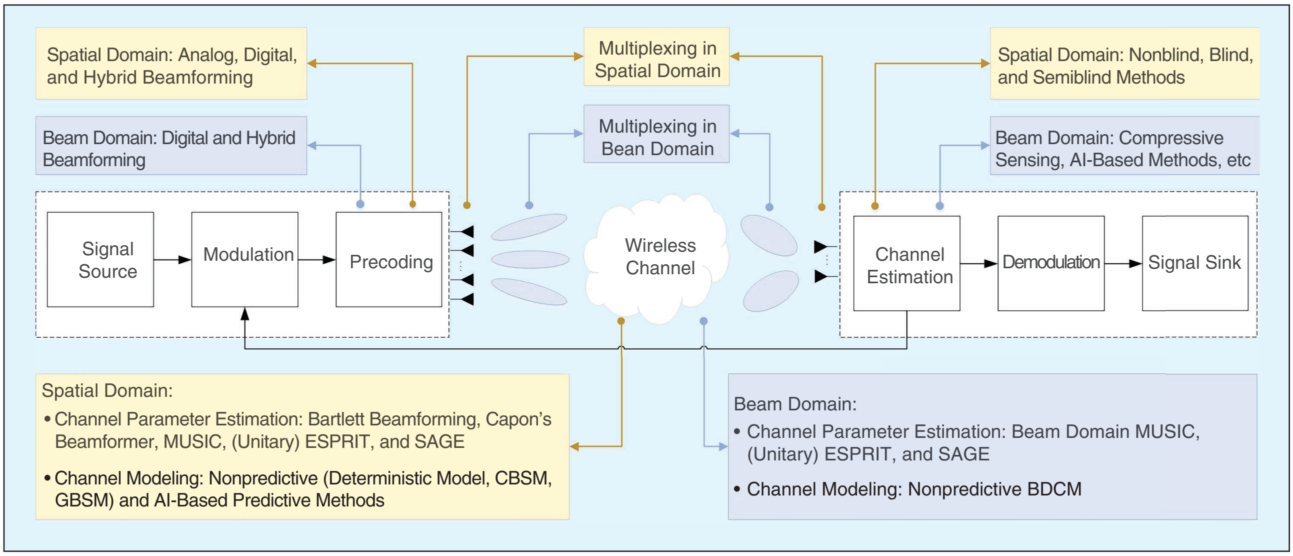

FIGURE 5 Working flowchart of ultramassive MIMO.

Benefiting from the beamforming, it handles multiple dedicated directional signals rather than uncontrolled multipath signals.

In ultramassive MIMO system, the utilization of beam domain multiplexing has not been extensively studied. Taking the new channel characteristics of ultramassive MIMO channel into consideration, it needs to be noted that the interference-rejecting and dynamic beamforming techniques are required.

Precoding/Beamforming

Traditional precoding/beamforming techniques rely on the accurate acquisition of CSI. With known CSI, precoding is operated at the Tx side to adjust data streams for better adaption to the channel. It can be used to focus radiation energy into target direction, thus to improve energy efficiency and decrease multiuser interference. Before transmission, precoding can be performed by postmultiplying the channel matrix with a precoding matrix. The precoding matrix varies with different methods. There are linearly zero forcing (ZF), block diagonalization, and matched filter (MF) methods, and nonlinear dirty paper coding, vector perturbation, and lattice-aided methods [13]. ZF is the simplest method, and when the BS antenna number grows, it performs as well as the interference-free system. However, the computational complexity to get the matrix pseudoinverse is high. MF can achieve high signal to interference plus noise ratio when BS antenna number scales up.

As analog beamforming utilizes analog phase shifters to acquire beamforming gain, it is not suitable for multiple data stream transmission. By using digital processing chain for each antenna element, full digital beamforming can deliver high energy efficiency, channel capacity, and relaxed hardware requirements. However, with mmWave and THz bands, the wide bandwidth requirement on digital-to-analog and analog-to-digital converters hinders the usage of this method. Hybrid beamforming, namely, analog–digital beamforming, has been proposed to provide low implementation complexity and reduced power consumption. It also eliminates CSI estimation. It consists of analog multibeam selection and blind estimation algorithm. It was indicated in [3] that with the utilization of beam domain MIMO technologies with hybrid precoding, near-optimal performance with dramatically reduced complexity can be achieved.

In ultramassive MIMO channels, the sparsity property is expected to approximate full digital beamforming performance. There are also AoA-based precoding/beamforming techniques that do not need CSI. However, the AoA estimation needs to be performed for data transmission. To settle the interference problem of closed users in signal separation, constant modulus algorithm, independent component analysis, etc., can be used. Distributed MIMO can efficiently exploit the diversity and offer excellent coverage. Cell-free ultramassive MIMO, facilitated with a large amount of distributive access points to serve small users, inherits advantages from both distributed MIMO and ultramassive MIMO. Considering the reduced computational complexity and the distributed implementation merit, conjugate beamforming is very useful for signal processing at distributed access points. It is an important candidate for a cell-free ultramassive MIMO network. However, the increased self-interference in forward-link transmission needs to be solved by either assigning pilots for each user or introducing pilot recovery technique.

Comparison of PHY Technologies in Spatial and Beam Domains

Resorting to the different channel characteristics in spatial and beam domains, principles of transmission technologies show some differences. The privileges of ultramassive MIMO technologies in the beam domain over the spatial domain are briefly illustrated in Table 1. The overall concerns of spatial domain data processing are the complexity and computing burden brought by the increased antenna array number. Besides providing reduced complexity, the execution of beam domain processing can also provide concise expression and alleviate hardware constrains, for example, in channel estimation.

Future Research Challenges

Ultramassive Antenna Array Configurations

An ultramassive linear array could stretch tens or hundreds of meters long at the sub-6-GHz frequency band. In practical implementation, this poses serious requirements on related infrastructures such as the antenna derrick. Besides, ULA can only offer azimuthal spatial resolution, while being unable to provide elevational coverage. To relax such pressures, more compact 3D array configurations can be used, such as planar array, circular array, and cylindrical array. However, the mutual coupling effect that may have an impact on beamforming needs to be mitigated. The utilization of mmWave and THz can also facilitate ultramassive antennas into a more compact size [14]. Besides the aforementioned centralized antenna array, there are also distributed antenna arrays. The antenna elements can be separately placed to improve signal coverage. As a special case of distributed array, block array is introduced to provide more flexibility for configuration. To avoid the intercell interference, cell-free massive MIMO was proposed. In a cell-free network, many access points controlled by a central processing unit are distributed coherently to serve many users with the same time and frequency resources [15]. It is foreseen as a promising network to clarify the boundary effect of conventional cellular networks and to provide huge energy and spectrum efficiencies with a simple signal process technique.

Holographic Massive MIMO and Reconfigurable Intelligent Surface

Considering that the channel capacity can grow monotonically with the increase of antenna number, holographic massive MIMO has been proposed to approach the upper bound limits of massive MIMO system. A reconfigurable intelligent surface (RIS) is a metasurface that can flexibly steer the signal transmission direction and improve signal coverage [15]. In recent years, there have been more works using massive array in RIS. It has been proposed that by facilitating enough antennas at the RIS, a continuous surface can be formed to be holographic RIS. Although this is an ideal case, the utilization of massive array is destined. With the intervention of RIS in ultramassive MIMO channel, related PHY technologies need to be changed correspondingly, including channel modeling, channel estimation, etc. In general, holographic massive MIMO and RIS are exciting and challenging research topics.

Beam Division in Temporal and Frequency Domains

It has been pointed out in [8] that, except dividing virtual beams in spatial domain, we can also divide beams in both temporal and frequency domains. Therefore, by using the joint virtual beams in the spatial-temporal-frequency domain, the sparsity property is more dominant to further reduce computational complexity. This is also beneficial for the ultramassive MIMO channel in high-mobility mmWave/THz band. The Doppler effect and high delay resolution can be well handled. The accuracy and complexity of the channel estimation can also be improved.

Beam Domain Channel Characterization and Modeling

Through reviewing existing literature, we find a lack of in-depth work regarding beam domain channel parameter estimation, channel characteristics analysis, and channel modeling of the ultramassive MIMO channel. As they are fundamentals for the development of spatial-temporal transmission and random access technologies, it is worth digging into 1) the definition of effective beam domain parameters and parameter estimation methods that consider ultramassive MIMO channel characteristics, 2) the manifestation of spatial domain channel characteristics in the beam domain and the exploration of other new beam domain channel characteristics with the combination of mmWave/THz in time-variant scenarios, and 3) the BDCMs that can accurately describe the beam domain channel characteristics with reduced complexity relative to GBSMs.

Large-Dimensional Computing Theory

A significant hindrance of the massive MIMO system is the overwhelming computational burden. With the increase of array elements, mathematical calculations in signal design, channel estimation, detection, resource allocation, etc., pose huge challenges to the ultramassive MIMO system. A flexible and efficient computational framework for large-dimensional computing theory is expected to support the development of the ultramassive MIMO system. The striving directions may be how to utilize the inherent features of massive data and the advantages of AI algorithms.

Conclusions

In this work, recent advances of 6G ultramassive MIMO techniques in both spatial and beam domains have been reviewed. Therein, ultramassive MIMO channel parameter estimation algorithms, channel characteristics, and channel models have been introduced as the foundations of further PHY technology design and evaluation. Channel estimation, spatial multiplexing, and precoding techniques have been surveyed with emphases on the transitions of data processing in the spatial domain into the beam domain, thus to provide better tradeoff between accuracy and complexity. However, more efforts need to be devoted to including new ultramassive MIMO characteristics into consideration and clarifying the impacts of system setups on global performance. Therefore, advanced PHY

TABLE 1 ***Advantages and challenges of ultramassive MIMO technologies in the beam domain.***

Technology	*Advantage*	*Challenge*
MPC parameter estimation	• Reduced complexity • Less sensitivity to array imperfection • Decreased SNR resolution threshold	• Full exploration of channel characteristic • Multi-dimensional parameter estimation
Channel modeling	• Reduced complexity • Linearly relationship with angle • Concise expression for system performance analysis	• Consideration of new channel characteristic • Tradeoff between accuracy and complexity
Channel estimation	• Reduced pilot overhead • Decreased computational complexity • Alleviated RF chain constraints	• Accuracy with limited RF chains • Exploration of efficient algorithm
Spatial multiplexing	• Improved array gain • Improved multiplexing gain	• Necessities of interference-rejecting and dynamic beamforming techniques

techniques can be proposed to reap the utmost benefits of ultramassive MIMO communication system.

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References

[1] X.-H. You et al., "Towards 6G wireless communication networks: Vision, enabling technologies, and new paradigm shifts," *Sci. China Inf. Sci.*, vol. 64, no. 1, Jan. 2021, Art. no. 110301, doi: 10.1007/s11432-020-2955-6.

[2] C.-X. Wang, J. Huang, H. Wang, X. Gao, X.-H. You, and Y. Hao, "6G wireless channel measurements and models: Trends and challenges," *IEEE Veh. Technol. Mag.*, vol. 15, no. 4, pp. 22–32, Dec. 2020, doi: 10.1109/MVT.2020.3018436.

[3] J. Brady, N. Behdad, and A. M. Sayeed, "Beamspace MIMO for millimeter-wave communications: System architecture, modeling, analysis, and measurements," *IEEE Trans. Antennas Propag.*, vol. 61, no. 7, pp. 3814–3827, Jul. 2013, doi: 10.1109/TAP.2013.2254442.

[4] L. You, X. Gao, G. Y. Li, X.-G. Xia, and N. Ma, "BDMA for millimeter-wave/terahertz massive MIMO transmission with per-beam synchronization," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 7, pp. 1550–1563, Jul. 2017, doi: 10.1109/JSAC.2017.2699100.

[5] C.-X. Wang, Z. Lv, X. Q. Gao, X.-H. You, Y. Hao, and H. Haas, "Pervasive wireless channel modeling theory and applications to 6G GBSMs for all frequency bands and all scenarios," *IEEE Trans. Veh. Technol.*, vol. 71, no. 9, pp. 9159–9173, Sep. 2022, doi: 10.1109/TVT.2022.3179695.

[6] R. Feng, C.-X. Wang, J. Huang, X. Gao, S. Salous, and H. Hass, "Classification and comparison of massive MIMO propagation channel models," *IEEE Internet Things J.*, vol. 23, no. 9, pp. 23,452–23,471, Dec. 2022, doi: 10.1109/JIOT.2022.3198690.

[7] M. D. Zoltowski, M. Haardt, and C. P. Mathews, "Closed-form 2-D angle estimation with rectangular arrays in element space or beamspace via unitary ESPRIT," *IEEE Trans. Signal Process.*, vol. 44, no. 2, pp. 316–328, Feb. 1996, doi: 10.1109/78.485927.

[8] A. M. Sayeed, "Deconstructing multiantenna fading channels," *IEEE Trans. Signal Process.*, vol. 50, no. 10, pp. 2563–2579, Oct. 2002, doi: 10.1109/TSP.2002.803324.

[9] Y. Wu, X. Gao, S. Zhou, W. Yang, Y. Polyanskiy, and G. Caire, "Massive access for future wireless communication systems," *IEEE Wireless Commun.*, vol. 27, no. 4, pp. 148–156, Aug. 2020, doi: 10.1109/MWC.001.1900494.

[10] N. Wang, W. Li, P. Wang, A. Alipour-Fanid, L. Jiao, and K. Zeng, "Physical layer authentication for 5G communications: Opportunities and road ahead," *IEEE Netw.*, vol. 34, no. 6, pp. 198–204, Nov. 2020, doi: 10.1109/MNET.011.2000122.

[11] X. Wei, C. Hu, and L. Dai, "Deep learning for beamspace channel estimation in millimeter-wave massive MIMO systems," *IEEE Trans. Commun.*, vol. 69, no. 1, pp. 182–193, Jan. 2021, doi: 10.1109/TCOMM.2020.3027027.

[12] S. Chen, S. Sun, G. Xu, X. Su, and Y. Cai, "Beam-space multiplexing: Practice, theory, and trends, from 4G TD-LTE, 5G, to 6G and beyond," *IEEE Wireless Commun.*, vol. 27, no. 2, pp. 162–172, Apr. 2020, doi: 10.1109/MWC.001.1900307.

[13] F. Rusek et al., "Scaling up MIMO: Opportunities and challenges with very large arrays," *IEEE Signal Process. Mag.*, vol. 30, no. 1, pp. 40–60, Jan. 2013, doi: 10.1109/MSP.2011.2178495.

[14] H. Q. Ngo, A. Ashikhmin, H. Yang, E. G. Larsson, and T. L. Marzetta, "Cell-free massive MIMO versus small cells," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1834–1850, Mar. 2017, doi: 10.1109/TWC.2017.2655515.

[15] M. Matthaiou, O. Yurduseven, H. Q. Ngo, D. Morales-Jimenez, S. L. Cotton, and V. F. Fusco, "The road to 6G: Ten physical layer challenges for communications engineers," *IEEE Commun. Mag.*, vol. 59, no. 1, pp. 64–69, Jan. 2021, doi: 10.1109/MCOM.001.2000208.

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