Near-Field MIMO Communications for 6G: Fundamentals, Challenges, Potentials, and Future Directions

Mingyao Cui, Zidong Wu, Yu Lu, Xiuhong Wei, and Linglong Dai

The authors present the fundamentals of near-field communications and the metric to determine the near-field ranges in typical communication scenarios.

Abstract

Extremely large-scale antenna array (ELAA) is a common feature of several key candidate technologies for sixth generation (6G) mobile networks, such as ultra-massive multiple-input-multiple-output (UM-MIMO), cell-free massive MIMO, reconfigurable intelligent surface (RIS), and terahertz communications. Since the number of antennas is very large for ELAA, the electromagnetic radiation field needs to be modeled by near-field spherical waves, which differs from the conventional planar-wave-based radiation model of 5G massive MIMO. As a result, near-field MIMO communications will become essential in 6G wireless networks. In this article, we systematically investigate the emerging near-field communication techniques. First, we present the fundamentals of near-field communications and the metric to determine the near-field ranges in typical communication scenarios. Then we investigate recent studies specific to near-field communications by classifying them into two categories: techniques addressing the challenges and those exploiting the potentials in near-field regions. Their principles, recent progress, pros, and cons are discussed. More importantly, several open problems and future research directions for near-field communications are pointed out. We believe that this article will inspire more innovations in this important research topic of near-field MIMO communications for 6G.

Introduction

The sixth generation (6G) mobile networks are promising to empower emerging applications, including holographic video, digital replica, and so on. For fulfilling these visions, tremendous research efforts have been made to develop new wireless technologies to meet the key performance indicators (KPIs) of 6G, which are far superior to those of 5G [1]. For instance, thanks to the enormous spatial multiplexing and beamforming gain, ultra-massive multiple-input multiple-output (UM-MIMO) and cell-free massive MIMO (CF-MIMO) are expected to accomplish a 10-fold increase in the spectral efficiency for 6G [1]. Furthermore, by dynamically manipulating the wireless environment through thousands of antennas, reconfigurable intelligent surface (RIS) brings new possibilities for capacity and coverage enhancement [2]. Moreover, millimeter-wave (mmWave) and terahertz (THz) UM-MIMO can offer abundant spectral resources for supporting 100× peak data rate improvement (e.g., terabits per second) in 6G mobile communications [3]. Despite being suitable for different application scenarios with various KPIs, all the above technologies, including UM-MIMO, CF-MIMO, RIS, and THz communications, share a common feature: They all usually require a very large number of antennas to attain their expected performance; hence, extremely large-scale antenna arrays (ELAA) are essential to these different candidate technologies for 6G.

Compared to massive MIMO, the key technology in 5G networks, ELAA for 6G not only means a sharp increase in the number of antennas but also results in a fundamental change of the electromagnetic (EM) characteristics. The EM radiation field can generally be divided into far-field and radiation near-field regions. The boundary between these two regions is determined by the Rayleigh distance, also called the Fraunhofer distance [4]. Rayleigh distance is proportional to the product of the square of array aperture and carrier frequency [4]. Outside the Rayleigh distance, it is the far-field region, where the EM field can be approximately modeled by *planar waves*. Within the Rayleigh distance, the near-field propagation becomes dominant, where the EM field has to be accurately modeled by *spherical waves*.

Since the number of antennas is not very large in 5G massive MIMO systems, the Rayleigh distance of up to several meters is negligible. Thus, existing 5G communications are mainly developed from far-field communication theories and techniques. However, with the significant increase of the antenna number and carrier frequency in future 6G systems, the near-field region of ELAA will expand by orders of magnitude. For instance, a 3200-element ELAA at 2.4 GHz was developed in [2]. With an array size of 2 m × 3 m, its Rayleigh distance is about 200 m, which is larger than the radius of a typical 5G cell. Accordingly, near-field MIMO communications will become essential components in future 6G mobile networks where the spherical propagation model needs to be considered, which is obviously different from the existing far-field 5G systems. Unfortunately, the near-field propagation introduces several new challenges in ELAA systems, which should be identified and addressed to empower 6G communications.

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The authors are with the Department of Electronic Engineering, Tsinghua University, China. The corresponding author is Linglong Dai.

In this article, we systematically investigate the recent near-field communication techniques for 6G. The key features of this article can be summarized as follows:

- To begin with, the fundamental differences between far-field and near-field communications are explained. Comparatively speaking, the planar wavefront in the far-field can steer the signal energy toward a specific physical *angle*. On the contrary, the near-field spherical wavefront achieves energy focusing on *both angle and distance*. Moreover, the Rayleigh distance that quantifies the boundary between far-field and near-field regions is introduced, and its derivation is explained in detail. Based on this derivation, we further extend the classical Rayleigh distance, for MIMO channels with a direct base station (BS)-user equipment (UE) link, to the one for RIS-aided communications, where a cascaded channel is utilized for presenting the BS-RIS-UE link.
- Additionally, we investigate the emerging near-field communication techniques by classifying them into two types: techniques addressing the challenges and those exploiting the potentials in near-field regions. On one hand, as most techniques specific to far-field often suffer from severe performance loss in the near-field area, the first type of techniques aims to compensate for this loss, such as near-field channel estimation and beamforming. On the other hand, the second kind of study has revealed that the nature of near-field spherical wavefront can also be exploited to provide new possibilities for capacity improvement. The principles, recent progress, pros, and cons of these two categories of research are discussed in detail.
- Finally, several open problems and future research directions for near-field communications are pointed out. For example, the improvement of Rayleigh distance considering various communication metrics need to be analyzed, artificial intelligence (AI) is expected to enable high-performance near-field transmissions with low complexity, and hybrid far- and near-field communications also require in-depth study.

Fundamentals of Near-Field Communications

In this section, we first present the differences between far-field and near-field communications. Then we identify the principle to determine the boundary between the far-field and near-field regions in several typical application scenarios.

Far-Field Communications vs. Near-Field Communications

The critical characteristics of far-field and near-field communications are shown in Fig. 1. We consider an uplink communication scenario, while the discussions in this article are also valid for downlink scenarios. The BS is equipped with an ELAA. A widely adopted metric to determine the boundary between far-field and near-field regions is the Rayleigh distance, also called the Fraunhofer distance [4]. When the communication distance between the BS and UE (BS-UE distance) is larger than the Rayleigh distance, the UE is located in the far-field region of the BS. Then EM waves impinging on the BS array can be approximately modeled as planar waves. In contrast, when the BS-UE distance is shorter than the Rayleigh distance, the UE is located in the near-field region of the BS. In this region, EM waves impinging on the BS array must be accurately modeled as spherical waves [5].

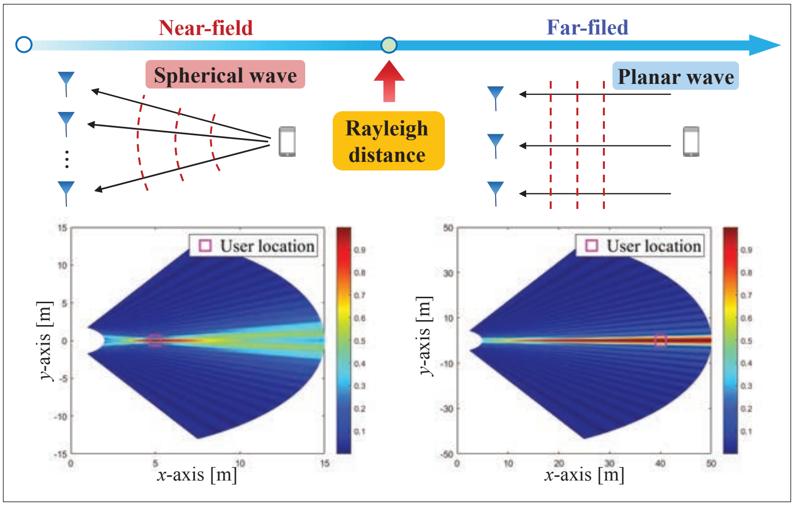

FIGURE 1. Far-field planar wavefront vs. near-field spherical wavefront. The plots at the bottom illustrate the normalized received signal energy in the physical space achieved by near-field beamfocusing (bottom left) and far-field beamsteering (bottom right).

More precisely, the planar wave is a long-distance approximation of the spherical wave. In far-field regions, the phase of EM waves can be elegantly approximated by a ***linear*** function of the antenna index through Taylor expansion. This concise linear phase forms a planar wavefront only related to an incident angle. Accordingly, by the utilization of planar wavefronts, far-field beamforming can steer the beam energy toward a specific angle over different distances, which is also called beamsteering, as shown in the bottom right of Fig. 1. Unfortunately, this concise linear phase fails to thoroughly reveal the information of spherical waves. In near-field regions, the phase of spherical waves should be accurately derived based on the physical geometry, which is a ***nonlinear*** function of the antenna index. The information of the incident angle and distance in each path between BS and UE is embedded in this nonlinear phase. Exploiting the extra distance information of spherical wavefronts, near-field beamforming is able to focus the beam energy on a specific location, where energy focusing on both the angle and distance domain is achievable, as shown in the bottom left of Fig. 1. Due to this property, beamforming in the near-field is also called beam focusing.

The differences between far-field planar wavefronts and near-field spherical wavefronts bring several challenges and potentials to wireless communications, which are detailed in the following sections.

Rayleigh Distance

The most crucial premise for near-field communications is quantifying the boundary between the far-field and near-field regions (i.e., the Rayleigh distance). Generally, the classical Rayleigh distance is proportional to the square of the array aperture and the inverse of the wavelength. Its derivation can be summarized as follows [4]. The true phase of the EM wave impinging on a BS antenna has to be calculated based on the accurate spherical wave model. In far-field sce-

The true phase of the EM wave impinging on a BS antenna has to be calculated based on the accurate spherical wave model. In far-field scenarios, this phase is usually approximated by its first-order Taylor expansion based on the planar wavefront model.

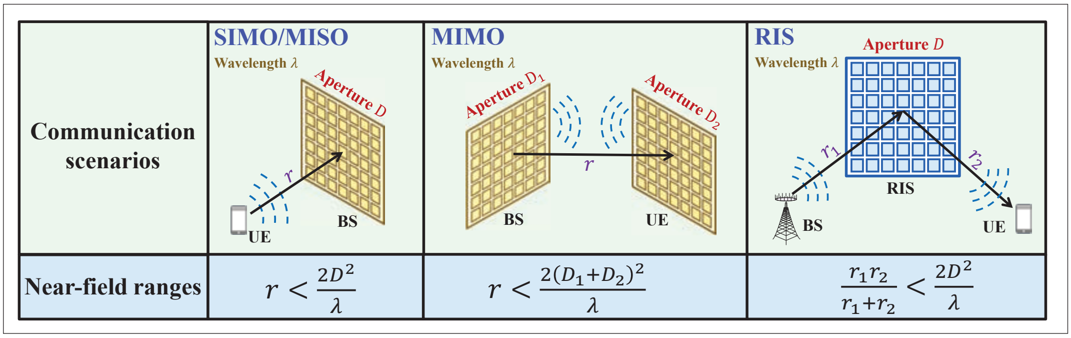

FIGURE 2. Near-field ranges for typical scenarios.

narios, this phase is usually approximated by its first-order Taylor expansion based on the planar wavefront model. This approximation results in a phase discrepancy, which increases when the distance decreases. When the largest phase discrepancy among all BS and UE antennas reaches $\pi/8$, the distance between the BS array center and the UE array center is defined as the Rayleigh distance. Accordingly, if the communication distance is shorter than the Rayleigh distance, the largest phase discrepancy will be larger than $\pi/8$. In this case, the far-field approximation becomes inaccurate, and thus the near-field propagation needs to be utilized.

Based on this definition, the near-field ranges for single-input multiple-output (SIMO), multiple-input single-output (MISO), and MIMO communication systems can be obtained. As illustrated in Fig. 2, the near-field range of SIMO/MISO scenarios is precisely determined by the classical Rayleigh distance, which is proportional to ***the square of BS array aperture***. For the MIMO scenario, since ELAAs are employed at two sides of the BS-UE link, both the BS array aperture and the UE array aperture contribute to the Rayleigh distance; that is, the near-field range is proportional to ***the square of the sum of BS array aperture and UE array aperture***.

Interestingly enough, we further extend the conventional Rayleigh distance derived in SIMO/MISO/MIMO systems to that in RIS-aided communication systems, as shown in Fig. 2. Unlike SIMO/MISO/MIMO channels with a direct BS-UE link, the cascaded BS-RIS-UE channel in RIS systems comprises the BS-RIS and RIS-UE links. Therefore, when calculating phase discrepancy, the BS-RIS distance and the RIS-UE distance need to be added. Then, capturing the largest phase discrepancy of $\pi/8$, the near-field range in RIS systems is determined by ***the harmonic mean of the BS-RIS distance and the RIS-UE distance***, as shown in Fig. 2. It can be further implied from Fig. 2 that as long as any of these two distances is shorter than the Rayleigh distance, RIS-aided communication is operating in the near-field area. Therefore, near-field propagation is more likely to happen in RIS systems.

With the dramatically increased number of antennas and carrier frequency, the near-field range of ELAA considerably expands. For instance, we have recently fabricated a 0.36 m aperture ELAA at 28 GHz. If it is employed in SIMO/MISO scenarios, its near-field range is about 25 m. When both transmitter and receiver are equipped with this array, the near-field range becomes 100 m. Moreover, if this ELAA works as a RIS with a BS-RIS distance of 50 m, the near-field propagation should be accepted once the RIS-UE distance is shorter than 50 m. In summary, near-field communications come to be an indispensable part of future 6G.

Challenges of Near-Field Communications

The near-field propagation causes several challenges to wireless communications; hence existing 5G transmission methods specific for far-field suffer from severe performance loss in near-field areas. Technologies recently developed for addressing these challenges are discussed in this section.

Near-Field Channel Estimation

Challenge: Accurate channel estimation is required to attain the expected performance gain of ELAA. As the number of channel paths is usually much smaller than that of antennas, channel estimation methods with low pilot overhead generally design suitable codebooks to transform the channel into a sparse representation. For the far-field codebook, each codeword of the codebook corresponds to a planar wave associated with one incident angle. Ideally, each far-field path can be represented by *only one* codeword. With this far-field codebook, the angle-domain representation of the channel can be obtained, and it is usually sparse due to the limited paths. Then beam training and compressed sensing (CS) methods are applied to estimate far-field channels with low pilot overhead accurately. However, this far-field planar-wave codebook mismatches the actual near-field spherical-wave channel. This mismatch indicates that a single near-field path should be jointly described by *multiple* codewords of the far-field codebook. Accordingly, the near-field angle-domain channel is not sparse anymore, which inevitably leads to the degradation of channel estimation accuracy. Therefore, near-field codebooks suitable for near-field channels need to be carefully created.

Recent progress: Some recent works have been endeavored to design near-field codebooks utilizing spherical wavefronts [5, 6]. In [6], the entire two-dimensional physical space is uniformly divided into multiple grids. Each grid is associated with a near-field array response vector, and all of these vectors construct the near-field codebook. With this codebook, the joint angle-distance information of each near-field path is extracted. Then the near-field channel can be estimated by CS methods with low pilot overhead. However, with the decrease of BS-UE distance, the near-field propagation becomes dominant, and the distance information gradually becomes more crucial.

Therefore, we can conceive the intuition that the grids should be sparse far away from the ELAA but dense near the ELAA. Without considering this intuition, the codebook in [6] is hard to use to attain satisfactory channel estimation performance in the entire near-field region. To this end, by minimizing the largest coherence among codewords in the near-field codebook, the authors in [5] mathematically prove this intuition (i.e., the angle space could be uniformly divided, while the distance space should be non-uniformly divided). As shown in Fig. 3, the shorter the distance, the denser the grid. With the help of this non-uniform codebook, a polar-domain sparse channel representation and corresponding CS-based algorithms are proposed in [5] to accomplish accurate channel estimation in both near- and far-field areas.

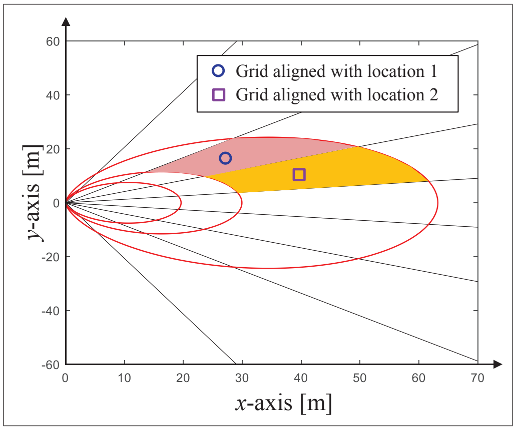

FIGURE 3. Near-field codebook with non-uniform grids.

Near-Field Beam Split

Challenge: In THz wideband systems, ELAA might encounter a beam split phenomenon, also known as beam squint and spatial-wideband effect. Existing THz beamforming architecture often employs analog phase shifters (PSs) [7], which usually tune the same phase shift for signals at different frequencies. Nonetheless, the actual phase of the EM wave is the product of the signal propagation delay and the *frequency-dependent* wave number. As a result, the signal propagation delay can be compensated through a phase shift adequately only for a narrowband signal. Phase errors are introduced for the other frequencies, thus causing the beam split effect. In fact, the impact of beam split on far-field and near-field propagations also differs.

In far-field, beam split leads to the fact that beams at different frequencies are transmitting toward different angles, as shown in the left of Fig. 4. For near-field beam split, however, beams are focused at both different angles and various distances due to the split of spherical waves, as shown in the right of Fig.4. Both far-field and near-field beam splits severely reduce the received signal energy of frequency components misaligned with the user location. Over the years, extensive works have been proposed to mitigate far-field beam split by tuning *frequency-dependent* phase shifts with planar wavefronts through true-time-delay-based (TTD-based) beamforming instead of PS-based beamforming. Unfortunately, due to the discrepancy between planar and spherical waves, these schemes addressing the far-field beam split no longer work well in the near-field, posing challenges to THz ELAA communications.

Recent progress: Recently, a few efforts have tried to overcome the near-field beam split effect. In [8], a variant of chirp sequence is utilized to design the phase shifts for flattening the beam focusing gain across frequencies with the sacrifice of the maximum beam focusing gain. This method can slightly alleviate the near-field beam split effect, but its spectral efficiency degrades as well when the bandwidth is very large, as the beams are still generated by PSs. To this end, a phase-delay focusing (PDF) method is proposed in [9] exploiting TTD-based beamforming. To further illustrate, the BS ELAA is first partitioned into multiple sub-arrays. The UE is assumed to be located in the far-field area of each small sub-array but within the near-field range of the ELAA. Then one TTD line is inserted between each sub-array and the radio frequency (RF) chain to realize frequency-dependent phase shifts. Finally, the frequency-dependent phase variations across different sub-arrays induced by spherical wavefronts are compensated by the inserted TTD line. As a result, beams over the working band are focused at the target UE location [9].

In conclusion, the first solution [8] follows the PS-based beamforming, which is easy to implement, but the achievable performance is unsatisfactory. The second scheme [9] can nearly eliminate the near-field beam split effect but requires the implementation of TTD lines. In fact, although deploying TTD lines by optical fibers has been demonstrated in the optical domain, this kind of deployment is nontrivial to be extended to THz ELAA communications. Fortunately, recent advances in graphene-based plasmonic waveguides provide low-cost solutions for implementing TTD lines at high frequencies [7].

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Potentials for Near-Field Communications

Unlike the aforementioned works for dealing with the performance degradation in the near-field, some recent studies have surprisingly revealed that 6G networks can also benefit from near-field propagation. In this section, we discuss those studies exploiting the potentials of near-field propagation to improve communication performance.

Single-User Capacity Improvement

Potential: The spatial multiplexing gain of MIMO communications considerably increases with the transition from far-field regions to near-field regions. In far-field MIMO communications, the line-of-sight (LoS) channel can be represented by a rank-one matrix, where the spatial degrees of freedom (DoFs) are very limited. In contrast, the near-field LoS channel can be rank-sufficient derived from the geometric relationship under the spherical propagation model. The increased rank indicates dramatically improved spatial DoFs in the near-field region. Precisely, based on the expansion of prolate spheroidal wave functions, it is proved in [10] that near-field spatial DoFs are proportional to the product of the BS and UE array apertures and inversely proportional to the BS-UE distance. This conclusion is further improved in [11] by meticulously designing the beamfocusing vectors of the BS and UE arrays. As shown in Fig. 5, the DoFs increase from 1 to 20

Fortunately, near-field beam focusing enjoys the capability of energy focusing on the joint angle-distance domain. Hence, near-field SDMA could generate beams with spherical wavefronts to simultaneously serve users located at similar angles but different distances.

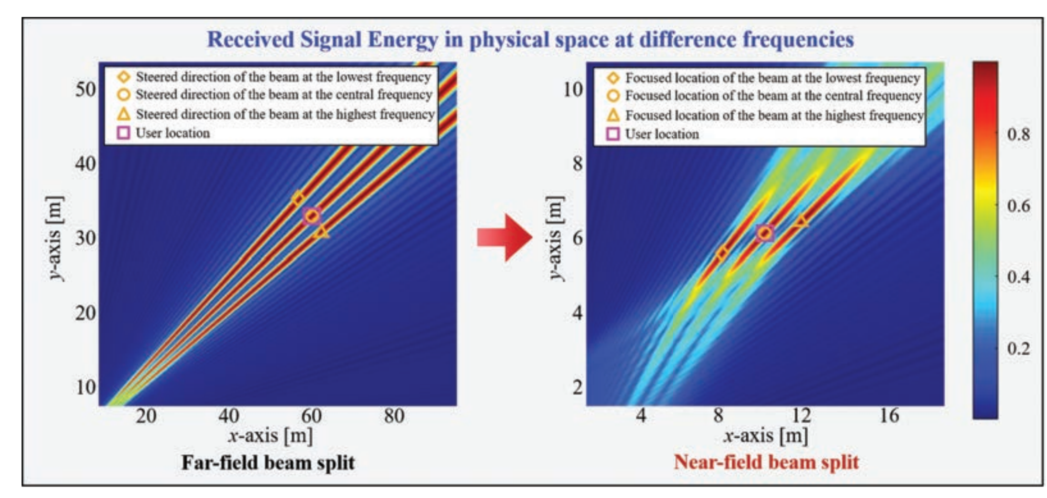

FIGURE 4. This figure illustrates the far-field beam split effect (left) and the near-field beam split effect (right). Far-field beam split makes beams at different frequencies transmit toward different directions, while near-field beam split makes beams at different frequencies be focused on various locations.

when the BS-UE distance decreases from 350 m to 10 m. Thanks to the increased DoFs, the near-field LoS path enables simultaneous transmission of multiple data streams by MIMO precoding, as opposed to the rank-one far-field LoS channel supporting only one data stream. The increased spatial DoFs can be exploited as an additional spatial multiplexing gain, which offers a new possibility for significant capacity enhancement.

Recently, some novel precoding architectures have been proposed to leverage these extra near-field DoFs for MIMO capacity enhancement [12, 13]. First, distance-aware precoding (DAP) was developed in [12]. Unlike classical hybrid precoding with a fixed and limited number of RF chains (e.g., 2 or 4 fixed RF chains), the DAP architecture could flexibly adjust the number of RF chains to match the distance-related DoFs, which is achieved by deploying a selection network to configure each RF chain as active or inactive. For instance, in the far-field region, only one RF chain is activated for data transmission. When communication distance is decreasing to 10–20 m, around 20 activated RF chains are enough to adapt to the DoFs, as shown in Fig. 5. By doing so, the number of transmitted data streams dynamically matches the DoFs. Simulations demonstrate the DAP could significantly increase the spectral efficiency, while its energy efficiency is comparable with hybrid precoding. To avoid the utilization of extra RF chains, another effort to harvest the potential spatial multiplexing gain in near-field areas is the widely spaced multi-subarray (WSMS) precoding [13]. In this architecture, the sub-arrays are widely spaced to enlarge the array aperture, artificially creating the expansion of the near-field region. Compared to classical hybrid precoding, the number of sub-arrays and the sub-array spacing should be additionally designed in the WSMS architecture. To this end, [13] first assumed planar-wave propagation within each sub-array and spherical-wave propagation across different sub-arrays similar to [9]. Then [13] jointly optimized the number of sub-arrays, their spacing, and the precoding matrix for maximizing the achievable rate. Simulations demonstrate that WSMS could achieve nearly 200 percent higher spectral efficiency than classical hybrid precoding.

Multi-User Capacity Improvement

Potential: Near-field propagation is also able to improve capacity in multi-user (MU) communications. To increase the spectral efficiency in MU-MIMO communications, space-division multiple access (SDMA) is widely considered to distinguish users through orthogonal or near-orthogonal spatial beams. Thus, multiple users can share the same time and frequency resources. For far-field SDMA, utilizing beamsteering to generate beams with planar wavefronts can distinguish users at different angles. A downside is that users located at similar angles will severely interfere with each other, and thus cannot simultaneously access the network through far-field SDMA. Fortunately, near-field beam focusing enjoys the capability of energy focusing on the joint angle-distance domain. Hence, near-field SDMA could generate beams with spherical wavefronts to simultaneously serve users located at similar angles but different distances, as shown in Fig. 6. The distance information of spherical wavefronts supplies a new utilizable dimension for multi-user access; thus, near-field SDMA can also be regarded as location-division multiple access (LDMA).

Recent progress: Taking advantage of the capability of beamfocusing, the authors in [14] studied the near-field multi-user transmission considering fully digital precoding, hybrid precoding, and transmissive reconfigurable metasurface (RMS). By optimizing the sum rate in multi-user systems through alternating optimization, all considered precoding architectures can naturally generate beams with spherical wavefronts to distinguish users located at similar angles but different distances. The simulation results demonstrate that near-field propagation has the potential of enhancing multi-user capacity.

Future Research Directions

In this section, several future research directions for near-field communications are pointed out.

Near-Field Communication Theory

Improvement of Rayleigh Distance: As a widely adopted quantification of near-field range, Rayleigh distance is attained in terms of phase discrepancy. For communication metrics directly affected by phase discrepancy, such as channel estimation accuracy, Rayleigh distance can accurately capture the degradation of these metrics when applying far-field transmission schemes in the near-field region. On the contrary, some metrics are directly influenced by other factors instead of phase discrepancy; for example, capacity is determined by beamforming gain and channel rank. Accordingly, classical Rayleigh distance probably cannot capture the performance loss of these metrics well. To this end, several recent works have endeavored to improve classical Rayleigh distance in terms of some vital communication metrics. For instance, an effective Rayleigh distance (ERD) is derived in [9] for the accurate description of beamforming gain loss and capacity loss. Nevertheless, ERD is only valid for MISO communications, while more discussion should be made to improve Rayleigh distance in more practical scenarios under more general metrics (e.g., channel rank and energy efficiency in MIMO and RIS systems).

Near-Field Transmission Technologies

AI-Aided Near-Field Communications: Different from far-field communications, the transmission algorithms for near-field communications are more complex. To be specific, since extra grids on the distance domain are required, as mentioned earlier [5], the size of near-field codebooks is usually much larger than that of far-field codebooks, leading to high-complexity channel estimation and beamforming. Moreover, the *nonlinear* phase characteristics of spherical waves make the design of near-field beam training and precoding algorithms more complicated than that in far-field areas. AI-based transmission methods are promising to address these problems since they can mine the features of near-field environments through *nonlinear* neural networks. Currently, there are plenty of works elaborating on AI-based far-field transmissions (references are not provided here since the number of references is limited in this magazine), while AI-based near-field transmissions have not been well studied.

RIS-Aided Near-Field Communications: Compared to MIMO communications, the near-field propagation becomes even more dominant and complex in RIS-aided systems. In MIMO communications, based on the spherical propagation model, the EM waves form *spherical* equiphase surfaces at the receiver. On the contrary, in RIS-aided systems, the phase of received EM waves is accumulated by the propagation delays through the BE-RIS and RIS-UE links. Based on the geometry relationship, the equiphase surfaces become *ellipses* in the near-field range instead of spherical. Accordingly, the research on beamfocusing [15], channel estimation, and multiple access techniques taking into account this ellipses-equiphase property are required for RIS-aided near-field communications.

Hybrid Far- and Near-Field Communications: In practical systems, communication environments usually exist with both far-field and near-field signal components. First, in multi-user systems with multi-path channels, some users and scatterers may be far away from the BS while others are located in the near-field region of the BS, which constitutes a hybrid far- and near-field (hybrid-field) communication scenario. Additionally, it is worth mentioning that the Rayleigh distance is proportional to frequency. Thus, in an ultra-wideband or frequency-hopping system with a very large frequency span, its near-field range varies dramatically across the bandwidth. Chances are that the signal components at low frequencies may operate in far-field regions, while those at high frequencies with larger Rayleigh distances are propagating in the near-field areas, which also contributes to hybrid-field communications. Consequently, the above factors make hybrid-field communications practical and crucial in future 6G networks. Thus, hybrid-field transmission techniques handling both far-field and near-field signal components deserve in-depth study.

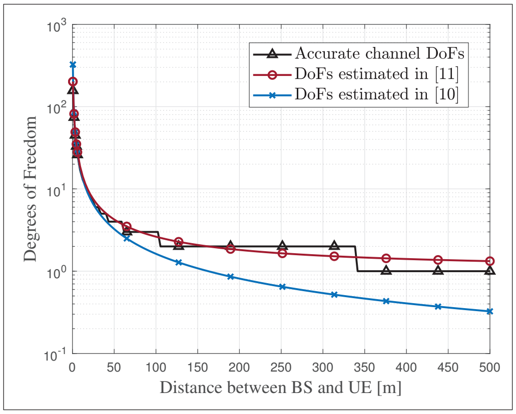

FIGURE 5. The spatial DoF increases in the near-field region. (Simulation codes can be found at http://oa.ee.tsinghua.edu.cn/dailinglong/publications/publications.html.)

Except for near-field propagation, the spatial non-stationarity effect is another fundamental characteristic of ELAA compared to 5G massive MIMO, where different scatterers and users are visible to different portions of the ELAA. This effect leads to the fact that only a part of the ELAA can receive the spherical EM waves radiated by a scatterer or a user.

Spatial Non-Stationarity Effect on Near-Field Communications: Except for near-field propagation, the spatial non-stationarity effect is another fundamental characteristic of ELAA compared to 5G massive MIMO, where different scatterers and users are visible to different portions of the ELAA. This effect leads to the fact that only a part of the ELAA can receive the spherical EM waves radiated by a scatterer or a user. The angular power spectral and average received power rapidly vary over the ELAA. Recently, there have been intensive works dealing with the non-stationarity effect and near-field propagation simultaneously [6]. However, the impact of non-stationarity on other emerging near-field communications has not been well studied, such as RIS-aided systems and hybrid-field communications.

Hardware Development

To verify the effectiveness of near-field transmission technologies, hardware developments and over-the-air experiments are of great significance. For example, for alleviating the near-field beam split effect, TTD lines need to be meticulously designed in the THz domain. The hardware developments of WSMS and DAP architectures are worth carrying out to exploit the near-field spatial DoFs. Furthermore, implementing these techniques still has to overcome several hardware impairment issues, including in-phase/quadrature imbalance, low-efficiency power amplifier at high frequency, and so on. All these challenges should be carefully addressed to enable the implementation of 6G near-field communications.

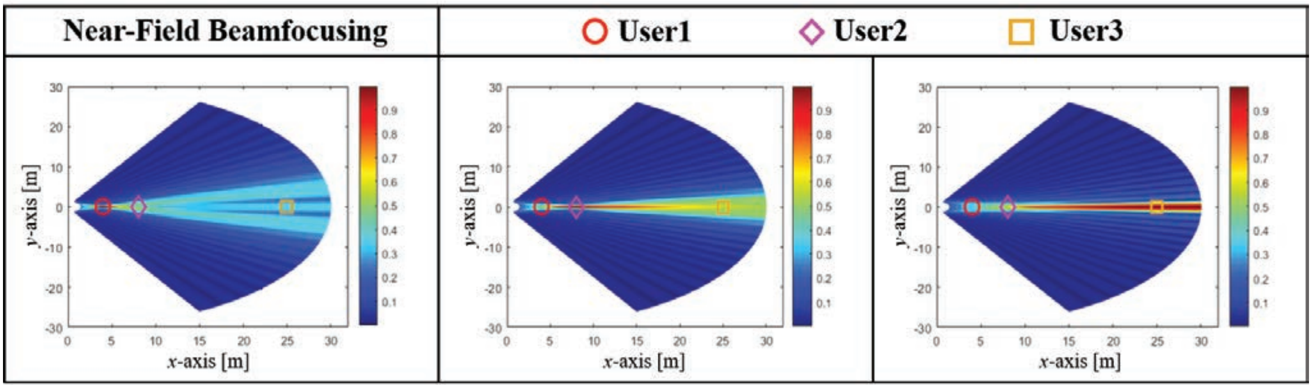

FIGURE 5. Near-field beamfocusing is able to serve multiple users in the same angle.

Conclusions

With the evolution from massive MIMO to ELAA, near-field propagation with spherical wavefront becomes indispensable in 6G networks, where conventional far-field propagation with planar wavefront is not valid anymore. In this article, we reveal that near-field propagation is a double-edged sword (i.e., it brings both challenges and potentials to 6G communications). We first introduce the nonlinear phase property of spherical waves and explain the derivation of near-field range in terms of phase discrepancy. Then we discuss the technical challenges of channel estimation and beam split caused by near-field propagation and present the recent solutions. In addition, some appealing works that exploit the capability of spherical waves to improve capacity are investigated. Several future research directions for near-field communications, such as improvement of Rayleigh distance and hybrid-field transmissions, are also highlighted, which are expected to inspire more innovations on 6G near-field MIMO communications.

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Biographies

Mingyao Cui (cmy20@mails.tsinghua.edu.cn) is an M.S. student in the Department of Electronic Engineering at Tsinghua University.

Zidong Wu (wuzd19@mails.tsinghua.edu.cn) is a Ph.D. student in the Department of Electronic Engineering at Tsinghua University.

Yu Lu (y-lu19@mails.tsinghua.edu.cn) is a Ph.D. student in the Department of Electronic Engineering at Tsinghua University.

Xiuhong Wei (weixh19@mails.tsinghua.edu.cn) is an M.S. student in the Department of Electronic Engineering at Tsinghua University.

Linglong Dai [F'21] (daill@tsinghua.edu.cn) is a professor at Tsinghua University. His current research interests include massive MIMO, RIS, wireless AI, and EIT. He received the IEEE Communications Society Leonard G. Abraham Prize in 2020, the IEEE Communications Society Stephen O. Rice Prize in 2022, and the IEEE ICC 2022 Outstanding Demo Award. He was listed as a Highly Cited Researcher by Clarivate from 2020 to 2022.