6G Wireless Communications: From Far-field Beam Steering to Near-field Beam Focusing

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***Abstract*—6G networks will be required to support higher data rates, improved energy efficiency, lower latency, and more diverse users compared with 5G systems. To meet these requirements, extremely large antenna arrays and high-frequency signaling are envisioned to be key physical-layer technologies. The deployment of extremely large antenna arrays, especially in high-frequency bands, indicates that future 6G wireless networks are likely to operate in the radiating near-field (Fresnel) region, as opposed to the traditional far-field operation of current wireless technologies. In this article, we discuss the opportunities and challenges that arise in radiating near-field communications. We begin by discussing the key physical characteristics of near-field communications, where the standard plane-wave propagation assumption no longer holds, and clarify its implication on the modelling of wireless channels. Then, we elaborate on the ability to leverage spherical wavefronts via beam focusing, highlighting its advantages for 6G systems. We point out several appealing application scenarios which, with proper design, can benefit from near-field operation, including interference mitigation in multi-user communications, accurate localization and focused sensing, as well as wireless power transfer with minimal energy pollution. We conclude with discussing some of the design challenges and research directions that are yet to be explored to fully harness the potential of this emerging paradigm.**

I. Introduction

Along with the commercial deployment of 5G networks, the next sixth-generation (6G) wireless networks are gradually evolving from a vision into concrete designs. Notably, 6G networks will be required to support immense throughput, with peak data rates of up to 1 Tbps; be highly energy efficient, with some applications expected to provide at least 1 terabit per Joule, and operate with ultra low latency, which in systems such as industrial control should be as low as 1 microsecond [1]. These performance requirements are necessary to support exciting new technologies of the 6G era, including the internet of everything, autonomous vehicles, and tele-medicine, in addition to conventional high-rate wireless communications.

In order to support the ambitious requirements of 6G wireless networks, extremely large antenna arrays and signaling in the high-frequency spectra, i.e., millimeter wave (mmWave) and sub-terahertz (THz) bands, are expected to be widely used. Extremely large antenna arrays can significantly improve spectral efficiency, which can be employed by transmitting Base Stations (BSs) [2] as well as by passive reconfigurable intelligent surfaces (RISs) [3]. On the other hand, high-frequency bands provide large available bandwidth, deviating from the congestion of the conventional wireless spectrum. The deployment of extremely large antenna arrays, especially in high-frequency bands, implies that future 6G wireless communications are likely to take place in the radiating near-field (Fresnel) region, as opposed to conventional wireless systems, which typically operate in the far-field regime. Specifically, the boundary between the radiating near-field region and the far-field region is dictated by the Fraunhofer limit [4], which is proportional to the square of the antenna aperture and inversely proportional to the signal wavelength. Consequently, as the antenna aperture of 6G transmitters increases and the signal wavelength decreases, the boundary can be several dozens and even hundreds of meters. For example, for an antenna with diameter of 1 meter transmitting at carrier-frequency of 30 GHz, the radiating near-field region extends to distances of up to 200 meters. Therefore, a major portion of the communications in 6G networks will take place in the radiating near-field region, as illustrated in Fig. 1.

While conventional wireless communications operate in the far-field, where electromagnetic (EM) wavefronts can be reliably approximated as planar, in the radiating near-field region the spherical shaping of the wavefront cannot be neglected. This property brings forth new opportunities and challenges for future wireless communications systems design. Spherical wavefronts can be exploited to generate *beam focusing*, providing beamforming capabilities that allow focusing signals on a specific spatial region. This is not achievable with traditional far-field beam steering, where signals can only be pointed towards a specific direction. While beam focusing can be leveraged to facilitate multi-user communication by, e.g., enabling new levels of interference mitigation [5], it also gives rise to new design and signal processing challenges. This stems from the fact that the radiating near-field spherical wavefront is inherently different from that observed in conventional far-field designs, and thus existing wireless communications models, schemes and results derived assuming far-field operation may no longer be valid. For example, the antenna gain reduces drastically when an antenna configured for the far-field is used for communication in the radiating near-field region [3]. This indicates the need to study the properties, potential benefits, and new design challenges, which arise from the radiating near-field operation of 6G wireless communications.

In this article, we overview the opportunities and challenges associated with the expected operation of 6G systems in the radiating near-field. We begin by presenting the distinct physical features of radiating near-field wireless communications, including spherical wavefronts and distance-aware channel models. Then, we elaborate on the possibility of exploiting the spherical wavefronts of the signals to implement

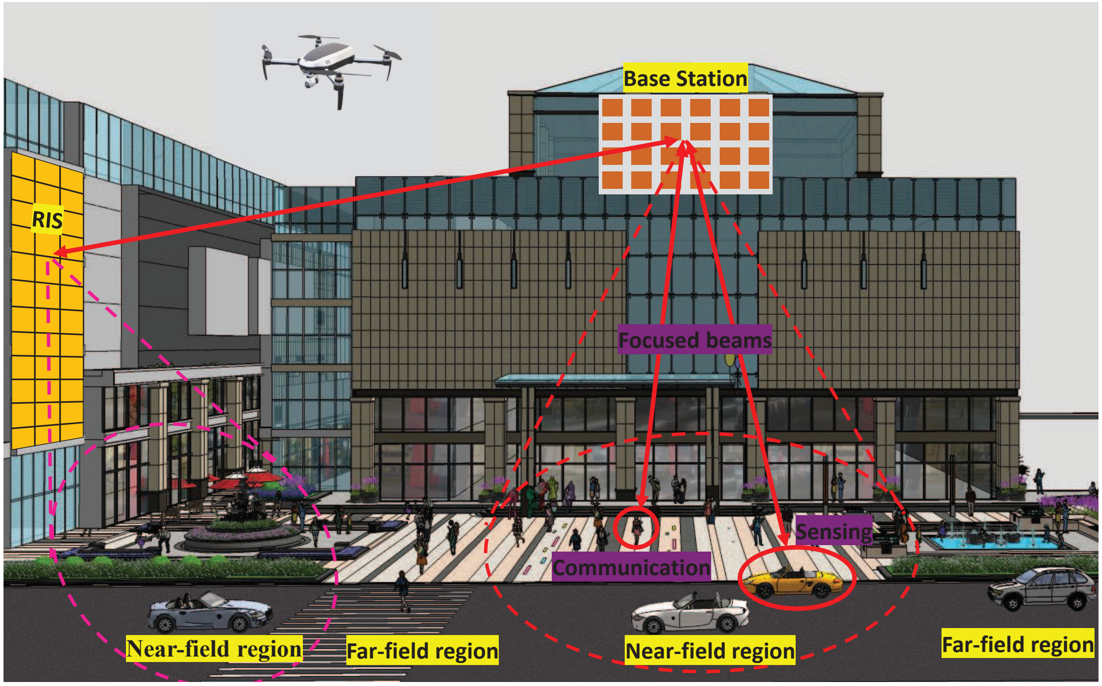

Fig. 1. An illustration of a near-field wireless communication system. The radiating near-field region can be up to tens of meters when the system operates in the mmWave frequencies with a large antenna array or RIS.

beam focusing, whose basic principle is presented using an example of phased arrays, and identify its potential advantages compared with far-field beam steering. To demonstrate the potential gains of beam focusing for 6G systems, we discuss three typical applications which rely on EM signaling and are likely to take place in the radiating near-field: (i) multi-user communications; (ii) localization and sensing; and (iii) wireless power transfer. In addition, using a near-field multi-user communication scenario as an example, we experimentally demonstrate the interference mitigation ability of beam focusing, showing that a near-field aware design allows to exploit its new degree of freedom (DoF) to mitigate co-channel interference in both angle and distance domains.

Next, we identify key design challenges and the corresponding potential research directions associated with radiating near-field wireless communications. We focus on the many unexplored algorithmic challenges arising from the need to realize beam focusing for 6G wireless networks, including near-field channel estimation; mis-focusing/beam split effect in near-field wideband communications. In addition, we discuss the opportunities and challenges of exploiting the high-rank property of near-field line-of-sight (LOS) multiple-input multiple-output (MIMO) channels to enhance the MIMO multiplexing gain, as well as hardware implementation challenges.

II. Radiating Near-field: Physical Features

A. *Spherical Versus Planar Waves*

As widely known, when antennas radiate EM waves in the surrounding free-space, they propagate exhibiting a spherical wavefront. However, in traditional wireless communications, the wavefront can be well approximated as being planar due to the large distances involved with respect to the operating wavelength. Nonetheless, such an approximation no longer holds in near-field radiative conditions, and, consequently, the wavefront impinging on the receiver is spherical. This peculiarity, visualized in Fig. 2, indicates that one can associate more information to an EM wave compared with far-field planar waves, bringing forth the possibility to improve communication performance or to enable other applications relying on EM radiation thanks to the availability of more diverse radiation patterns. Indeed, incident spherical wavefronts carry not only angular information, as typically happens in the far-field regime, but also distance information. This property can be exploited to, e.g., determine the position of a transmitting source without requiring an ad-hoc synchronization procedure and the subsequent exchange of several messages, as demonstrated in [6]. This position-awareness affects the channel model for wireless communications carried out in the radiating near-field, as discussed next.

B. *Near-Field Channel Model*

The near-field channel model has been mainly considered and analyzed for free-space propagation [7]. In classic far-field free-space channel models, the propagation distances from each antenna element to one target user are approximately identical, yielding the same path gain. Furthermore, antenna arrays share identical angle of arrival/departure, and thus the phase of each element in the array steering vector can be modelled as linear to the antenna index [8]. Unlike far-field free-space channel models, in the radiating near-field the aforementioned approximations do not hold, and the antenna elements have different distances with the target user and different angles of arrival/departure. Thus, in the near-field channel model, the wireless link from each antenna element to the target user has different path gain and phase variations.

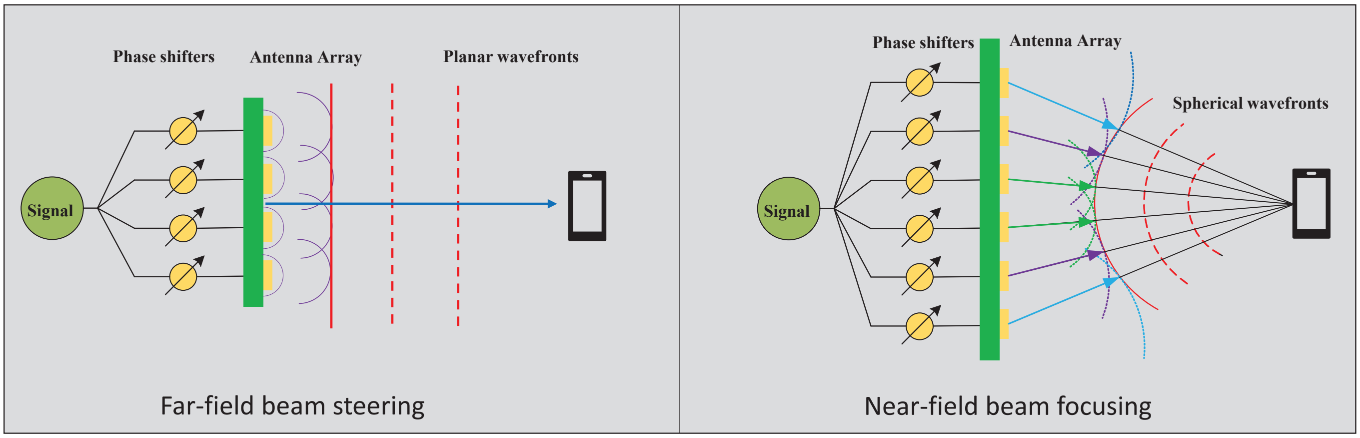

Fig. 2. Illustration of the principles of far-field beam steering and near-field beam focusing.

The characterization of multipath environments gives rise to additional channel modelling challenges. As previously discussed, 6G fosters the adoption of electrically large antenna arrays equipped with hundreds or even thousands of radiating elements. Thus, in contrast to traditional communication systems, the large array aperture makes the spatial channel properties experienced across the array non-stationary [9]. This means that some multipath components might be detected by certain elements of the array but not from the others and, thus, each set of antennas requires proper channel characterization. Traditional fading models are no longer suitable for describing such non-stationary channels. In addition, some of the surrounding scatterers may reside in the radiating near-field with respect to either the transmitter or the receiver, while others might lie in the far-field, so that hybrid models should be accounted for while representing the channel characteristics. Recently proposed modelling approaches, relying on Fourier plane-wave series expansion of the channel response [9] or by representing the environment using discrete coupled dipoles [10], allow to implicitly account for such hybrid scattering scenarios. Nonetheless, complete modelling of near-field wireless channels is still an active area of research.

III. Beam focusing

A. From Beam Steering to Beam Focusing

In conventional far-field wireless communications, transmit *beam steering* refers to an array signal processing technique where a multi-antenna transmitter sends EM signals to a specific direction, as shown in the left side of Fig. 2. Due to the EM wavefornts being planar, the transmitter can only control the relative angle towards which the most of the energy is radiated. In the radiating near-field region, the non-negligible spherical wavefront can be exploited to focus the radiated energy in a specific spatial location, i.e., not only by angle, but also by a specific depth along the direction of propagation, as shown in the right side of Fig. 2. This capability is referred to as *beam focusing*.

Similarly to beam steering, beam focusing is a transmit beamforming technique. As such, it is based on precoding of the outgoing signal to achieve a desired radiation pattern. In particular, to generate focused beams one must separately weight the spherical wave signals from each individual antenna such that they are added constructively at the desired focal point, yielding high signal strength, and have the radiated spherical wave signals added destructively in other points to, e.g., suppress interference. As in conventional beamforming, the most flexible design is achieved using fully-digital arrays, where one can individually control the outgoing waveform at each antenna, while typically resulting in costly and power hungry designs for large scale antennas and high frequency radiation. Nonetheless, beam focusing can also be achieved using hybrid analog/digital techniques and even with purely analog beamforming using, e.g., phased arrays as in Fig. 2, though typically with reduced flexbility compared with fully-digital arrays, especially when aiming for complex patterns with multiple focal points [5].

The ability to generate focused beams can be exploited to facilitate 6G wireless communications. The advantages of beam focusing when working in the near-field include:

- *Beam focusing provides a new DoF to shape the interference.* Beam focusing can not only control multi-user interference in the angle domain, as traditional beam steering, but also control the interference in the distance domain.
- *Beam focusing enables capacity-approaching near-field MIMO communications*. Capacity-approaching MIMO communication in near field leads to complex array phase profiles. As shown in [11], these can be efficiently approximated using a combination of simpler multiple focusing beams.

In the next section we illustrate some specific application examples of these advantages.

B. Application Scenarios

In the following, we list some of the typical scenarios in 6G networks where near-field aware beam focusing can be exploited to enhance performance:

- *Near-Field Multi-User Communications*: 6G BSs and access points will support a multitude of users, and are expected to involve non-orthogonal signalling. Such application scenarios result in multiple spectrum sharing users, which in turn is likely to result in notable interference. When the users are located in the radiating near-field region of the BS, co-channel interference can be mitigated via beam focusing, even when the users lie in the same relative direction [5]. This interference mitigation ability, which is not present in conventional far-field communications, gives rise to the possibility to support multiple coexisting orthogonal links, even at the same angles, thus allowing spatial user densification.

- *Near-Field Localization and Sensing*: The diverse heterogeneous nature of 6G networks indicates that some devices will utilize EM radiation not solely for communications, but also for probing the environment, e.g., for sensing and/or RF localization. Wireless localization and sensing are expected to be enhanced by the consideration of distance-aware channels. As an example, preliminary results have shown the possibility to perform holographic localization by exploiting the DoF offered by the spherical wavefront, so that positioning is boosted at an unprecedented scale thanks to the position information encapsulated in the wavefront [12].
- *Near-Field Wireless Power Transfer*: Wireless Power Transfer (WPT) is an emerging technology that allows an energy transmitter to charge multiple remote devices wirelessly, and has many potential applications in 6G networks [13]. Two core challenges in WPT are associated with the fact that energy transfer efficiency is relatively low due to the path loss degradation, and the need to avoid energy pollution, i.e., radiating energy at specific sensitive location. When WPT is carried out in the radiating near-field, beam focusing enables to jointly tackle these challenges, allowing to achieve efficient power transfer with minimal energy pollution, as shown in [13].

While the above applications arise from the main expected usages of EM radiation in 6G networks, there are also many other exciting application-oriented opportunities related to near-field communications. First, some emerging technologies aim at combining EM radiation for dual purposes. These include integrated sensing and communications, where beam focusing can greatly contribute to facilitating co-existence, and simultaneous wireless information and power transfer. An additional communication aspect which can benefit from beam focusing is physical-layer security, which aims at exploiting the physical features of wireless channels to convey information while keeping it concealed from eavesdroppers. In the conventional far-field case, beam steering and noise jamming are two commonly used signal processing tools to enhance the achievable secrecy rate. As the communication devices move to the radiating near-field, one can apply focused beams to focus the confidential messages on legitimate users and avoid information leakage to eavesdroppers. In this case, beam focusing can increase the secrecy rate and potentially enhance the energy efficiency of the whole system because jamming signals may be unnecessary.

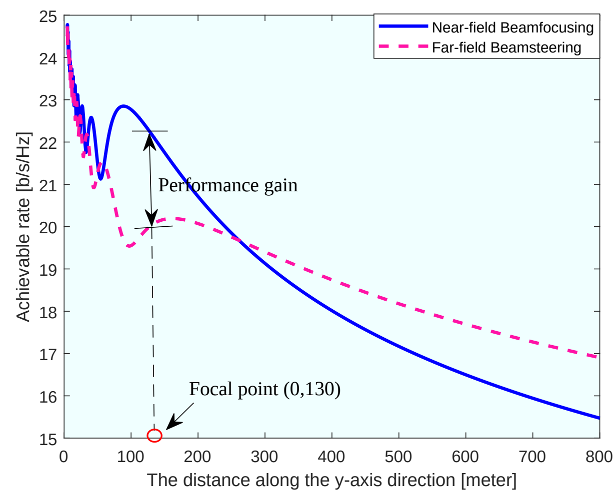

Fig. 3. Comparison of beam focusing and beam steering in terms of achievable rate.

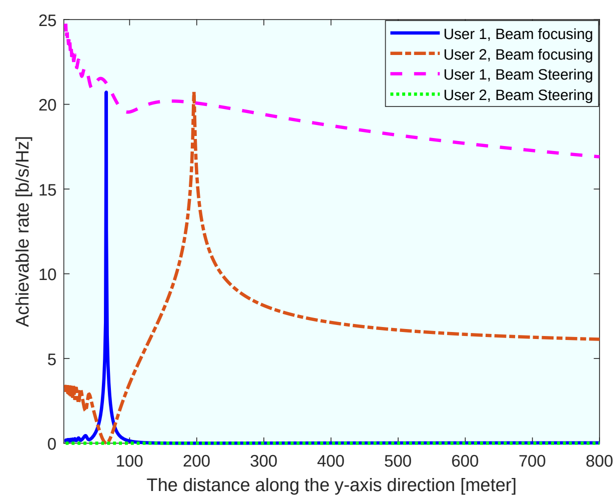

Fig. 4. Achievable rates per user versus location along the z-axis.

IV. Numerical Results

To demonstrate the potential of near-field beam focusing for 6G wireless communications, we simulate a multi-user communications setup, and present numerical results to illustrate the interference mitigation ability of beam focusing. We consider a near-field multi-user communication system where the BS is equipped with a fully-digital uniform linear array positioned in the x-axis, and two single-antenna users are placed in the y-axis, i.e., in the same angular direction. We consider an array of 512 half wavelength spaced antenna elements, and a carrier frequency of 30 GHz. Here, the Fraunhofer distance, i.e., the limit of the radiating near-field region, is approximately 1300 meters, covering a notable portion of the communication scenarios in 6G networks. In our simulation, we adopt the free-space LoS channel model to generate channels, where the maximum transmit power is set to be 1 W, and noise power is set to be -114 dBm.

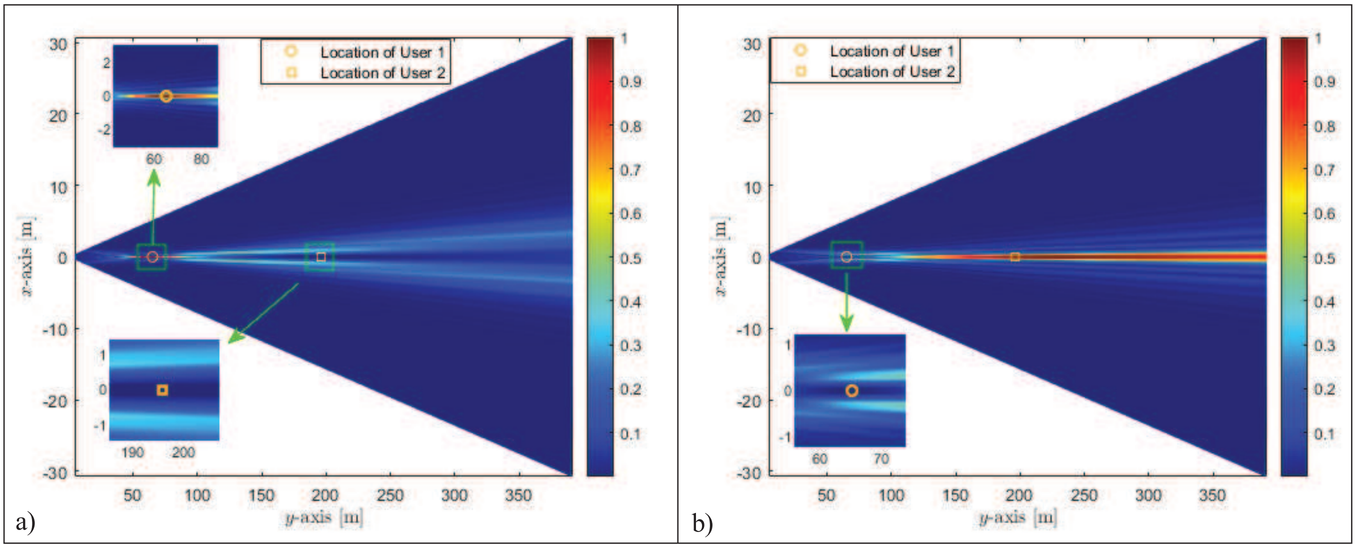

Fig. 5. The normalized signal power measurement of two focused beams: a) focused beam for user 1; b) focused beam for user 2.

We first illustrate the performance gain of beam focusing compared to beam steering for a single-user scenario. Fig. 3 shows the achievable rates when the receiver is located at different points along the y-axis, achieved by the fixed beam focusing and beam steering antenna configurations. The transmit pattern used for beam focusing is based on the scheme proposed in [5], and is pointed at the focal point of $(0, 130)$ meters, located in the near-field region. Beam steering is designed to steer the beam towards the same direction, i.e., along the y axis, with the objective of maximizing the received power. In Fig. 3, it is clearly shown that beam focusing can significantly increase the achievable rate compared to beam steering when the user is located in the proximity of the focal point. This is because beam steering is designed for the far-field scenario, resulting in performance loss when operating in near-field users due to channel mismatch. Moreover, we can observe that when the user is located in the y-axis but far away from the focal point, the achievable rate of beam focusing is lower than that of far-field beam steering, which implies the ability of beam focusing to reduce radiating interference.

Next, we demonstrate the advantage of beam focusing in distinguishing different users with the same angular direction. We again use the focusing scheme of [5] to design the beams to be focused at two near-field focal points located at $(65, 0)$ meters and $(195, 0)$ meters. We also design the far-field steered beams towards the same direction. Fig. 4 illustrates the achievable rates of each of the two users along the y-axis (when one user is moving along the y-axis, the other is fixed at the focal point), obtained using near-field beam focusing and far-field beam-steering antenna configurations. We observe in Fig. 4 that the peak achievable rates of each of the two users occur when they are located around their corresponding focal points, implying that the designed focused beams are all capable of yielding reliable communications with minimal degradation due to interference. In contrast, only one user can achieve a favorable rate for the far-field steer beams whereas the rate of the second user is approximately zero. This is because the two focal points have the same angular direction, and will generate strong interference, and thus beam steering allocates all the transmit power to one user with the better channel (i.e., smaller path loss) to maximize the sum-rate.

In Fig. 5 we visualize the co-channel interference mitigation ability of beam focusing. In particular, we plot the normalized signal power measurement of two focused beams on the xy-plane, where the focused beams are designed and used as in Fig. 4. From Fig. 5, we can observe that near-field focusing can not only enhance the signal strength at the focusing point, but also eliminate the co-channel interference to other users. For example, as shown in Fig. 5(a), the energy of the beam designed for user 1 is mainly focused on around user 1, and it does not generate co-channel interference to user 2, even if the two users lies in the same angular direction. Figs. 4 and 5 indicate that properly accounting for the expected near-field operation via dedicated beam focusing gives rise to new levels of interference mitigation not achievable in the conventional far-field, as one can not only control the multi-user interference in the angle domain, but also balance interference in the distance domain.

V. Design Challenges and Research Directions

As stated above, beam focusing enables sending signals on target regions with weak signal power leakage on other regions, making it an appealing technique for various 6G applications. However, approaching the performance gain of near-field beam focusing also requires to carefully address several challenges, giving rise to many interesting new research opportunities. In the following, we briefly discuss some of these potential challenges and unexplored research directions.

A. Channel Estimation

The ability to achieve focused beams heavily relies on accurate knowledge of the wireless channel. Since the aim is to have the signal energy concentrated on a small region around the desired focal points, beam focusing is more sensitive to inaccurate channel knowledge than far-field beam steering. Consequently, a proper channel modelling is of paramount importance, especially in the presence of non-stationary channels where classical models are no more adoptable.

Note that when moving-up in the frequency spectrum towards mmWave and sub-THz, the channel becomes sparse and is usually dominated by the LOS component so that channel state information (CSI) becomes tightly related to position estimation. In this scenario, attaining high-accuracy positioning and tracking performance can guarantee reliable beamfocusing capabilities.

B. Beam Misfocus/Split Issue

In order to focus beams on the target locations in near-field communications, the phase of each antenna should be designed to compensate for the signal transmission delay from the element to the target focal point. As a result, the phase of each transmit antenna element should depend on the transmission distance and frequency/wavelength, i.e., one should use frequency-selective precoding to achieve focused wideband beams. However, in common phased array-based communication systems, phase shifters are usually designed to be approximately frequency-flat within the communication band. Attempting to realize near-field wideband beam focusing using frequency-flat phase shifter hardware results in the so-called beam misfocus [14] or beam split [15] phenomenon, where the generated beams at different frequencies will focus on different locations. The misfocus effect limits the effective bandwidth of the phased array, resulting in poor performance of wideband communication systems. As a result, it is highly desirable to reduce or eliminate the beam misfocus problems, either via signal processing techniques or by design of flexible precoding hardware, to overcome the harmful effects of this phenomenon in near-field wideband communications.

C. MIMO Multiplexing Gain

The additional DoF of the near-field distance-aware channel model compared with its far-field counterpart gives rise to potential MIMO multiplexing gains. Unlike conventional far-field LOS MIMO channels, which are represented by rank-one matrices, the near-field LOS MIMO channel matrix, depending on the geometric configuration, can potentially become full-rank thanks to the richer information carried by spherical waves propagation. This implies that near-field LOS MIMO channels provide increased spatial DoF, which can be translated into multiplexing gain [11]. The exploitation of this channel property depends on the ability to address several design challenges. For once, the corresponding optimal precoding and decoding matrices are very sensitive to the geometric configuration of antennas normalized to the wavelength, thus making the CSI estimation process as well as hardware constraints more critical, especially at high frequency. As previously outlined, optimal precoding/decoding can be efficiently approximated by beam focusing operations, thus reducing the requirements on hardware.

D. Hardware Implementation

The operation of 6G wireless networks in the radiating near-field follows from the expected transition into high frequency communication and the envisioned proliferation of large scale MIMO arrays integrated onto BSs, access points, and RISs. The realization of these technologies, which naturally results in near-field operation whose potential is discussed in this article, is still subject to a multitude of implementation challenges. These include materials to be used, power amplifier efficiency, and the beam alignment between transmitter and receiver. In particular, the antenna structure needs to be able to reconfigure its focal spot or to form multiple focal areas, while also delivering desired performance for communication purposes. The hardware technology which can realize this operation with high-frequency signals is an area of ongoing research. For example, the efficiency of power amplifiers is typically frequency-dependent and tends to decrease as the carrier frequency increases. Therefore, it is of great significance to design high-efficient amplifier devices in future 6G wireless networks. Although these important hardware implementation challenges are not specific to near-field communications, they need to be carefully addressed for implementing efficient 6G near-field communication systems in practice.

VI. CONCLUSION

To date, wireless communications are mainly studied and designed in the far-field region, where the wavefronts can be well-approximated as planar. However, with the transition of 6G systems to high-frequencies combined with the usage of large-scale antennas, 6G devices are likely to operate in the radiating near-field region, where the conventional plane wave propagation assumption in far-field is no longer valid. In this article, we provided an overview of the opportunities and challenges of radiating near-field wireless communication systems. We first presented the key characteristics of near-field radiation where the spherical waveform propagation model holds, and clarified the new properties of the near-field channel model. Then, we discussed the emerging near-field beam focusing capability, highlighted its advantages for wireless communications, and pointed out its several appealing 6G-related applications. We concluded with some of the design challenges and potential research directions, which are expected to pave the way for implementing future 6G near-field wireless communication systems.

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