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Editorial:

Near-field communications: theories and applications

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Traditional wireless communication systems have extensively used far-field spatial resources. However, with the emergence of sixth-generation (6G) networks, the exploration and utilization of near-field resources have become imperative. These resources introduce novel physical spatial dimensions to wireless communication systems. By leveraging higher frequency bands—such as midband, millimeter-wave, and terahertz frequencies—and integrating technologies like reconfigurable intelligent surfaces (RISs), ultra-large-scale multiple input multiple output (MIMO), and cell-free networks, near-field communication (NFC) is set to become a critical enabler for 6G networks. This paradigm shift challenges the conventional far-field plane wave assumptions, necessitating a reevaluation of strategies for spatial resource management.

Although traditional systems have effectively exploited far-field spatial resources, the adoption of near-field resources in 6G networks presents opportunities to redefine wireless communication systems. This shift toward NFC catalyzes research into innovative technological paradigms. NFC has the potential to significantly improve spectrum efficiency, data transmission rates, and spatial precision, enabling advanced applications in domains such as augmented reality, high-precision localization, integrated sensing and communication (ISAC), and secure wireless power transfer. This work examines key factors influencing the development and application of NFCs.

1. Near-field propagation and channel modeling

With the progression to higher-frequency bands, the integration of extremely large-scale antenna arrays magnifies near-field effects. These effects include a transition from the conventional uniform plane wave propagation characteristic of the far field to nonuniform spherical wave propagation in the near field. Moreover, a shift occurs from spatial stationarity to pronounced spatial nonstationarity (SnS). The development of accurate near-field channel models is vital for effectively capturing these phenomena, ensuring improved system design and optimized application performance.

2. Enhanced spatial resource utilization

Advanced technologies, such as extremely large-scale RIS (XL-RIS) and extremely large-scale MIMO (XL-MIMO) systems, enable enhanced utilization of near-field spatial resources. By dynamically and precisely controlling electromagnetic propagation, these technologies expand spatial degrees of freedom and enable precise beam shaping. These advancements are expected to facilitate high-capacity, high-precision sensing and positioning, which are crucial for the realization of advanced 6G applications.

3. Hardware challenges

Designing and implementing hardware for NFC requires careful consideration of critical factors such

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as energy efficiency, cost, and complexity. The high-frequency signal processing necessary for NFC often results in increased power consumption, which drives the need for energy-efficient components and optimized circuit design methodologies. In addition, deploying ultra-large aperture and ultra-large-scale antenna arrays introduces significant challenges in terms of cost and complexity. As NFC hardware technology continues to advance, achieving a balance among energy efficiency, cost, complexity, and performance is essential to ensure widespread adoption and effective deployment across diverse applications.

4. Engineering and standardization

Near-field technologies constitute a pivotal research domain within the development of 6G communications, necessitating the redesign and optimization of relevant engineering and standardization frameworks. These frameworks address key elements, including the primary spectrum allocated for 6G, strategies to facilitate near-field propagation, network deployment methodologies, and standardization efforts. The emergence of ubiquitous near-field propagation environments is anticipated to introduce a transformative network paradigm for 6G. However, this shift presents a wide range of challenges that demand innovative and comprehensive solutions. Standardization and protocol design for NFCs focus on two primary aspects: near-field channel modeling and near-field communication protocols.

These areas emphasize the multifaceted nature of NFC, reflecting the need for advancements in modeling, technology, hardware development, and engineering practices, alongside standardization efforts.

Near-field communications possess transformative potential for the evolution of wireless technology, paving the way for diverse applications across consumer, industrial, and security domains. In this context, *Frontiers of Information Technology & Electronic Engineering* has organized a special issue titled "Near-Field Communications: Theories and Applications." This issue encompasses the foundational principles of near-field propagation, the development of relevant channel models, and the limitations faced by traditional mechanisms in near-field environments. In addition, it examines advancements in XL-MIMO channel research, simultaneous wireless information and power transmission (SWIPT) systems, and RIS, including STAR-RIS (simultaneous transmission and reflection intelligent surfaces), along with their applications in enhancing communication systems. This special issue includes 12 papers authored by researchers from around the globe, among which there are two review articles, five research articles, and five correspondences, offering a comprehensive exploration of the challenges and innovations in the field of near-field communications.

Near-field technology is increasingly recognized for its transformative potential in communication systems, positioning, and sensing, serving as a critical enabler for 6G telecommunications development. Yajun ZHAO and collaborators present a comprehensive survey of recent advancements in near-field technology research. Their study focuses on the fundamental principles of near-field propagation and the development of near-field channel models. Furthermore, they address the redesign and optimization of traditional mechanisms, such as channel estimation, beam training, and codebook design, while discussing innovative beam alignment techniques tailored to near-field propagation characteristics. The survey also highlights progress in engineering and standardization, covering primary 6G spectrum allocation, enabling technologies for near-field propagation and strategies for network deployment.

XL-MIMO technology, which provides vast spatial degrees of freedom through the deployment of numerous antennas, is emerging as a promising enabler for 6G mobile networks. Research on XL-MIMO channels is essential for the development, standardization, and application of this technology. Jianhua ZHANG and collaborators offer an overview of the challenges and ongoing research in XL-MIMO channel measurement, characterization, and modeling, with particular emphasis on near-field effects and SnS. The authors also examine various channel modeling methods that accurately describe these novel channel characteristics.

A STAR-RIS-assisted multi-user near-field wideband communication system has also garnered significant research interest. Zhao CHEN and collaborators propose a deep reinforcement learning (DRL) based framework for jointly designing active and passive beamforming in a multi-user downlink communication system assisted by a STAR-RIS. By accounting for the coupled phase shifts of the STAR-RIS and the hybrid beamforming structure of the base station (BS), they introduce a robust DRL algorithm, SD3, to address the joint beamforming design challenge. To mitigate the beam split issue, the researchers implement a delay–phase hybrid precoding structure to enhance wideband beamforming. In addition, they incorporate a soft-max operator to resolve the biased estimation problem commonly encountered in existing DRL algorithms.

With the development of millimeter-wave (mmWave) communication systems, large-scale RISs have emerged as a promising technology for enhancing signal strength and extending coverage. However, as the antenna scale and bandwidth increase, RIS-assisted wideband orthogonal frequency division multiplexing (OFDM) communication systems face notable challenges. These include the expansion of the near-field range and the beam split effect over high-frequency bands, which complicate the acquisition of channel state information (CSI). To address these issues, Boya DI and collaborators explore a RIS-assisted wideband OFDM communication system for users in the near–far field with unknown CSI. Using the beam split effect, they develop a beam-split-aware codebook capable of covering the near–far field with fewer codewords compared to conventional narrow-band codebooks. Based on this novel codebook, they propose a three-stage beam training mechanism with reduced training overhead.

Cunhua PAN and collaborators investigate the two-timescale design of XL-RIS-aided massive MIMO communication systems, considering the impact of visibility regions (VRs). Their study employs a spatially correlated channel model that accounts for VRs. A closed-form expression for the achievable user rate is derived, providing clarity to the optimization problem. In addition, they analyze how RIS VRs influence system complexity and simplify the user rate expression. The authors introduce a gradient-based algorithm, distinct from the genetic algorithm (GA), for solving the phase shift optimization problem. Their simulations and analyses of XL-RIS-aided massive MIMO systems demonstrate the impact of VRs on system performance from multiple perspectives.

Changjiang DENG and collaborators present a 2-bit dual-polarized electronic beam-scanning RIS designed specifically for 6G near-field applications. Their proposed element is based on a dual-polarized slot-coupled patch antenna, where each polarization uses a single single-pole four-throw (SP4T) switch to achieve 2-bit phase quantization. The two orthogonal polarizations operate independently. A 225-element RIS is fabricated and tested, showcasing main beam-scanning capabilities from −60° to +60° in both the *xoz* and *yoz* planes. The measured peak aperture efficiencies for the two polarizations are 40.1% and 38.3%, respectively. With its advantages of low cost, low power consumption, dual polarization, and 2-bit phase quantization, this RIS demonstrates significant potential for integration into 6G communication systems.

Lingxiang LI and collaborators address the joint estimation of position and velocity for multiple targets in a terahertz MIMO OFDM system operating in the near field. This scenario presents unique challenges due to spherical wavefront effects. To overcome these difficulties, the authors propose a CANDECOMP/PARAFAC (CP) decomposition based near-field localization (CP-NFL) algorithm for joint position and velocity estimation. The CP decomposition ensures uniqueness, and the computational complexity of the method scales linearly with the sum of the third power of the numbers of subcarriers, OFDM symbols, antennas, and targets.

Two-dimensional (2D) plane based XL-MIMO systems are widely studied and advocated in practical scenarios. Two promising hardware designs for XL-MIMO are the uniform planar array (UPA) based system, which features a discrete array aperture, and the 2D continuous aperture plane (CAP) based system, which uses a continuous array aperture. Evaluating the effective degree of freedom (EDoF) performance and exploring the performance limits of these designs are critical. Jiayi ZHANG and collaborators investigate the EDoF of XL-MIMO systems by comparing UPA-based and CAP-based designs under two representative near-field channel models: a scalar Green function based model and a dyadic Green function with triple polarization.

The growing number of wireless sensor devices poses persistent challenges related to battery replacement and power wiring. Long LI and collaborators address this issue by introducing a receiving metasurface designed for SWIPT systems. The metasurface employs frequency diversity to absorb electromagnetic (EM) energy at 5.8 GHz while transmitting sensor information at 2.45 GHz. This design offers advantages such as miniaturization, high isolation, and angle insensitivity, providing an innovative solution to power supply challenges for multiple sensors in the development of future digital urban infrastructure.

Jianyin CAO and collaborators establish a theoretical framework for optimizing the layout of low-altitude unmanned aerial vehicle (UAV) interference systems to improve spatial power synthesis efficiency at a specific point. UAV swarm scenarios are modeled to evaluate the impact of UAV platform performance and payload parameters on synthesis efficiency, particularly under near-field conditions. Results show that synthesis efficiency decreases significantly with increasing errors, especially at higher operating frequencies. Among various factors, positioning accuracy and time synchronization accuracy exert a greater impact on efficiency compared to attitude accuracy. In addition, a fiber-optic synchronization test scenario is constructed to evaluate spatial power synthesis efficiency under high-precision time synchronization.

Wireless communication is inherently susceptible to malicious jamming and eavesdropping due to the broadcast nature of wireless channels. XL-RIS technology has shown its potential to enhance physical layer security (PLS) and mitigate severe path loss. Gang YANG and collaborators explore an XL-RIS-empowered near-field PLS communication system that employs artificial noise to counter jamming and eavesdropping attacks. They formulate an optimization problem to improve security, and their proposed algorithm is extendable to other PLS communication systems with multiple eavesdroppers or statistical/partial CSI.

Hongfu MENG and collaborators propose an orbital angular momentum (OAM) multiplexing communication system using active uniform circular arrays to enable simultaneous five-mode transmission. Similar to active phased array systems, the receiving and transmitting modes can be reconfigured through phase shifter adjustments. Experimental results demonstrate that a 6-m OAM link supports the simultaneous transmission of five OAM streams, achieving a data rate of 3 Gb/s.

Finally, we would like to express our special gratitude to the authors, reviewers, and contributors for their support of this special issue, as well as to the editorial staff.

Yajun ZHAO holds a doctoral degree. Since 2010, he has served as a chief engineer at the Wireless and Computing Product R&D Institute of ZTE Corporation. Previously, he conducted wireless technology research at Huawei's Wireless Research Department. His current work focuses on 5G standardization and development of future mobile communication technologies, particularly 6G. He was instrumental in founding the RIS TECH Alliance, and serves as its deputy secretary general. In addition, he is a founding member and deputy leader of the RIS Task Group under the China IMT-2030 (6G) Promotion Group. To date, he holds more than 200 granted patents related to 4G LTE and 5G NR mobile communication technologies, over 20 of them being adopted into 4G/5G standards as standard essential patents. His research interests include RIS, near-field communications, spectrum sharing, flexible duplex, and coordinated multipoint transmission (CoMP).

Linglong DAI is a professor in the Department of Electronic Engineering at Tsinghua University, Beijing, China. He has published over 100 IEEE journal papers and more than 60 IEEE conference papers. He is also the holder of 21 granted patents and coauthored the book "mmWave Massive MIMO: a Paradigm for 5G" (Academic Press, Elsevier, 2016). He has received many awards, including six IEEE conference best paper awards at IEEE ICC/GLOBECOM/VTC, the *Electronics Letters* Best Paper Award in 2016, the IEEE ComSoc Asia–Pacific Outstanding Young Researcher Award in 2017, the IEEE ComSoc Leonard G. Abraham Prize in 2020, and the IEEE ComSoc Stephen O. Rice Prize and IEEE ICC Outstanding Demo Award in 2022. He was named an IEEE Fellow in 2021, and was supported by the National Science Fund for Distinguished Young Scholars in 2023. Recognized as a Highly Cited Researcher by Clarivate from 2020 to 2023, his research encompasses transmission theory and technology for wireless communications. His specific interests include massive MIMO, RIS, millimeter-wave and terahertz communications, machine learning for wireless communications, near-field communications, and electromagnetic information theory.

Jianhua ZHANG received her BS degree from North China University of Technology in 1994 and her PhD degree from Beijing University of Posts and Telecommunications (BUPT) in 2003. She was a guest PhD researcher at Hamburg University of Technology, Germany, from February to October, 2002. Currently, she is a professor at BUPT, a fellow of the Chinese Institute of Electronics and the China Institute of Communications, a deputy director of the State Key Laboratory of Networking and Switching Technology, and the director of the BUPT-CMCC Joint Research Center. She has authored over 300 papers in top IEEE journals and conferences, earning eight best paper awards. She has also published five books and three book chapters, and has been granted over 70 patents, receiving distinctions such as the Chinese Patent Excellence Award and a gold medal at the Geneva International Exhibition of Inventions. She is a recipient of the Young Female Scientist Award. She serves as an Executive Associate Editor-in-Chief of *Front Inform Technol Electron Eng*, an Associate Editor of *IEEE Trans Antenn Propag*, the Executive Editor-in-Chief of *Engineering*'s special issue, and the Lead Guest Editor of *IEEE Antenn Wirel Propag Lett*'s special issue. Previously, she served as an Associate Editor of *IEEE Wirel Commun Lett* and Lead Guest Editor of *IEEE Commun Mag*'s special issue. She has delivered over 30 invited talks, including a keynote at EuCAP and tutorials at IEEE WCNC, VTC, and ICC. As the 2016–2017 Chairwoman of the ITU-R IMT-2020 Channel Model Drafting Group, she contributed over 100 proposals to ITU-R, IMT, and 3GPP. She currently chairs the China IMT-2030 Technology Group's Channel Measurement and Modeling Subgroup. Her research focuses on 5G-A and 6G channel models, integrated sensing and communication (ISAC), XL-MIMO, RIS, and AI-enabled channel prediction, digital twin, and testing technologies.

Ping ZHANG received his PhD degree from BUPT in 1990. He is a professor with the School of Information and Communication Engineering at BUPT, the director of the State Key Laboratory of Networking and Switching Technology, a member of the IMT-2020 (5G) Experts Panel, and a member of the Experts Panel for China's 6G development. Previously, he served as a chief scientist of the National Basic Research Program (973 Program), an expert in the Information Technology Division of the National High-Tech R&D Program (863 Program), and a member of the Consultant Committee on International Cooperation of the National Natural Science Foundation of China. He is also an academician of the Chinese Academy of Engineering. His research spans a broad range of topics in wireless communications.