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Near-field communications: characteristics, technologies, and engineering

Key words: 6G; Near-field technology; Channel model; Codebook; Non-diffractive beams; Orbital angular momentum; Engineering and standardization

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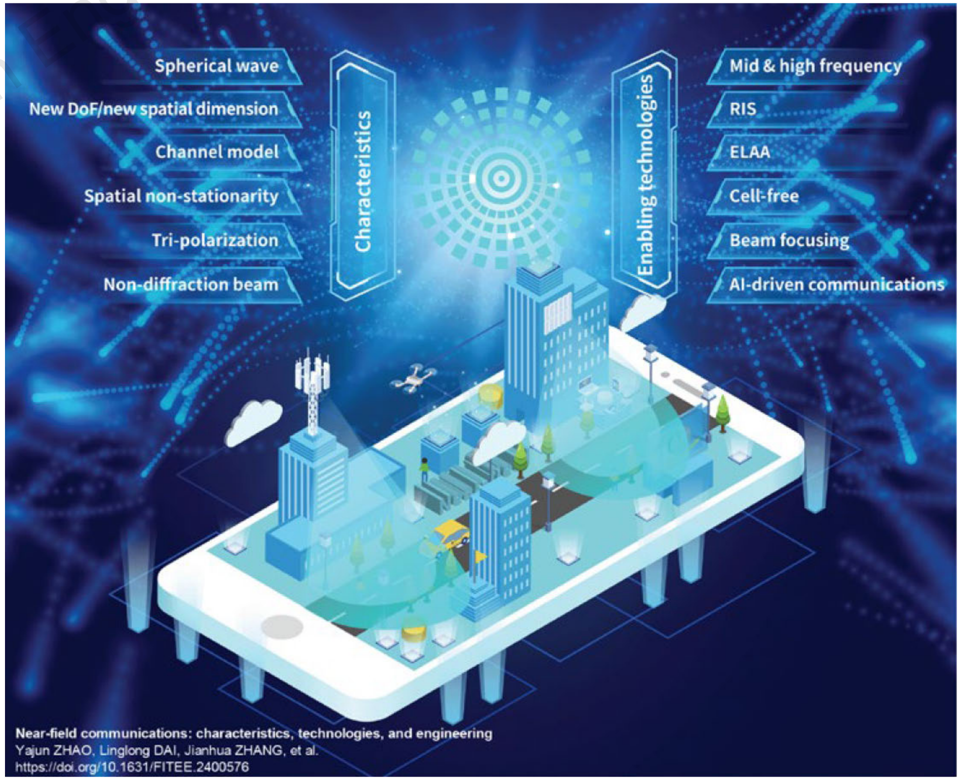

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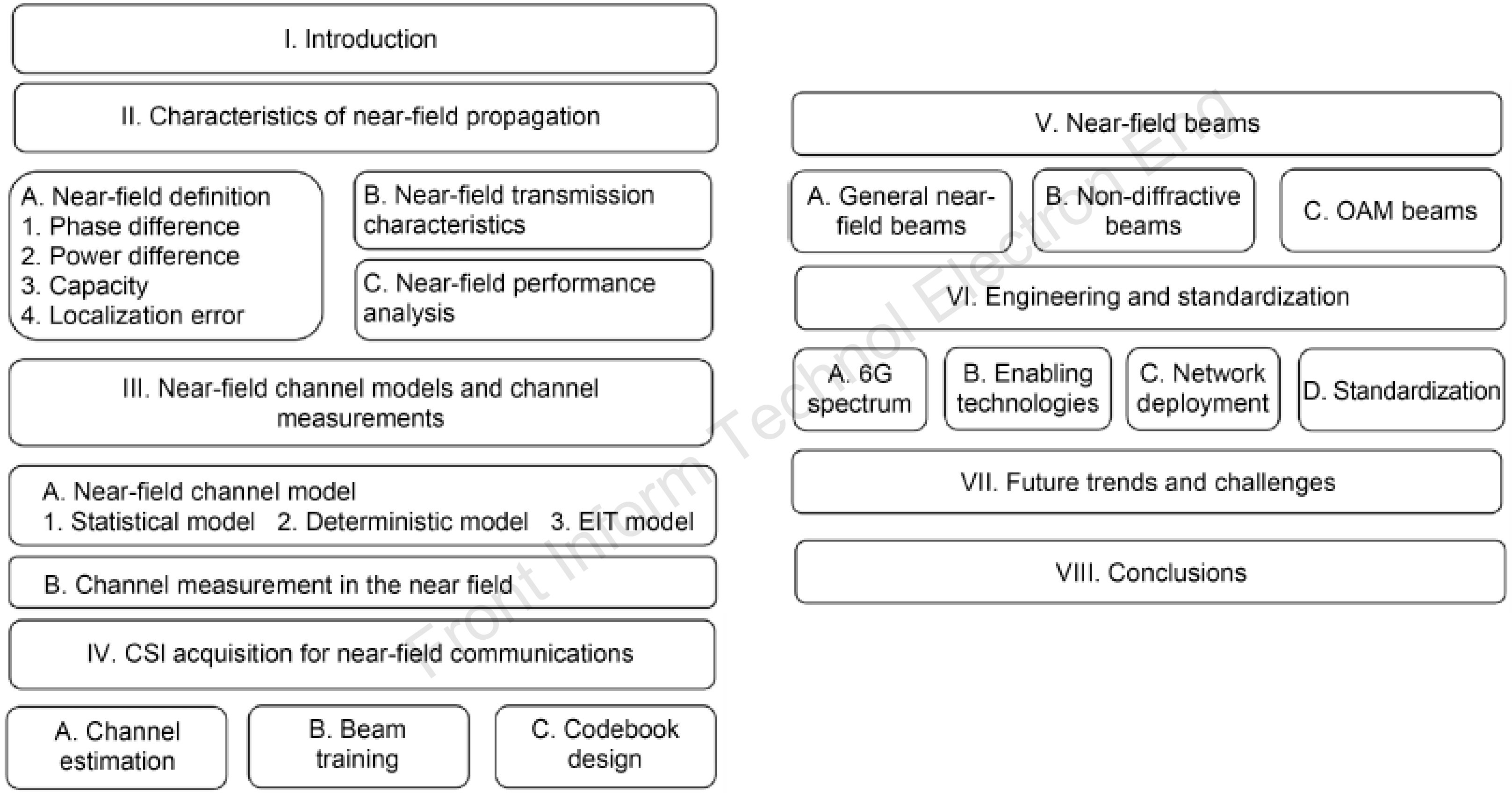
Introduction

- The extremely large-scale array (XL-array) encompasses ultra-massive MIMO (UM-MIMO), cell-free massive MIMO, and RIS, making it critical for meeting sixth-generation (6G) networks' technical benchmarks, such as peak data rates, spectral efficiency, positioning and sensing accuracy, and high connection density.
- 6G networks will use higher-frequency bands (above 6 GHz), including U6G (6.425–7.125 GHz), mid-band (7–24 GHz), millimeter-wave (mmWave), and sub-THz bands. These frequency ranges offer expanded bandwidths and improved propagation characteristics, effectively enabling next-generation cellular networks.
- The transition from massive MIMO to XL-array, coupled higher-frequency bands, involves more than just the increase of the number of antennas or array dimensions; it fundamentally alters electromagnetic (EM) propagation characteristics. The integration leads to a shift from traditional uniform plane-wave (UPW) propagation in the far field to nonuniform spherical wave (NUSW) propagation in the near field, as well as a transition from spatial stationarity to spatial non-stationarity (SnS).
- Near-field technology is increasingly recognized due to its transformative potential in communication systems, establishing it as a critical enabler for 6G telecommunication development.
- While near-field technologies have made substantial progress in academic research, engineering, and standardization, a comprehensive review addressing the engineering and standardization aspects is still lacking.

Main ideas

- This review presents a detailed survey of recent advancements in near-field communication research, with the main ideas outlined as follows:
  - First, we detail the fundamentals of near-field propagation, including definitions, transmission characteristics, and performance analysis.
  - Next, we examine near-field channel models and measurement results, covering deterministic, stochastic, and EM information theory-based models. We provide insights into the latest progress in channel testing, detailing the practical performance and limitations of these models.
  - Then, we provide a thorough analysis of channel state information (CSI) acquisition mechanisms tailored to near-field communications, encompassing channel estimation, beam training, and codebook design.
  - Following that, we introduce novel beams enabled by near-field effects, including non-diffractive beams (Bessel beams and Airy beams) and OAM beams, discussing their hardware architecture and signal processing workflow, and highlighting their transformative potential in near-field communication systems.
  - In addition, we highlight engineering and standardization progress, exploring key topics such as the primary 6G spectrum, enabling technologies for near-field propagation, and network deployment strategies.
  - Finally, we introduce several future research directions related to near-field technologies, which have the potential to significantly impact system design.

Structure of the survey



I. Introduction

II. Characteristics of near-field propagation

A. Near-field definition
1. Phase difference
2. Power difference
3. Capacity
4. Localization error

B. Near-field transmission characteristics

C. Near-field performance analysis

III. Near-field channel models and channel measurements

A. Near-field channel model
1. Statistical model 2. Deterministic model 3. EIT model

B. Channel measurement in the near field

IV. CSI acquisition for near-field communications

A. Channel estimation

B. Beam training

C. Codebook design

V. Near-field beams

A. General near-field beams

B. Non-diffractive beams

C. OAM beams

VI. Engineering and standardization

A. 6G spectrum

B. Enabling technologies

C. Network deployment

D. Standardization

VII. Future trends and challenges

VIII. Conclusions

Fig. 1 Structure of the survey

Near-field definition

- The near-field communication definitions from four perspectives:
  - Phase difference perspective
  - Power difference perspective
  - Capacity perspective
  - Localization error perspective

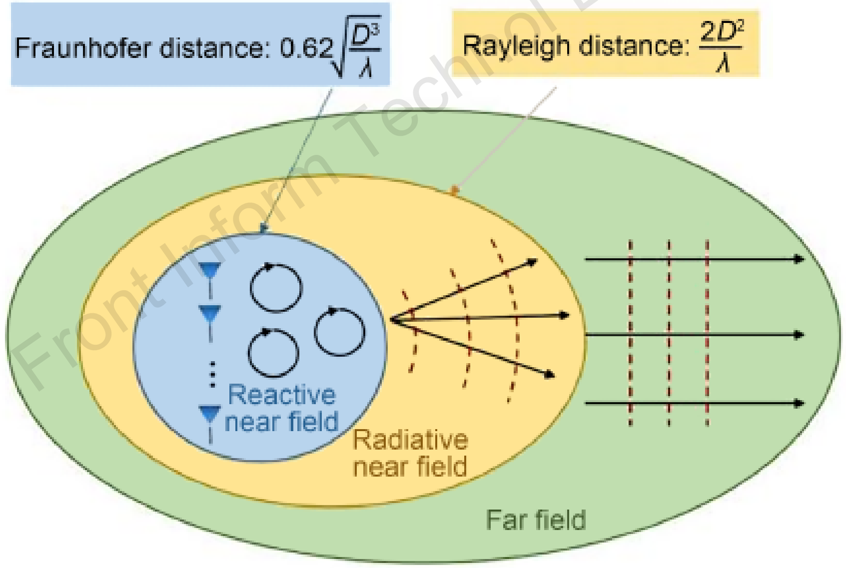


Fig. 2 Boundaries of various propagation regions and characteristics of near-field and far-field wavefronts

Physical characteristics

- Near-field communication exhibits several distinctive physical characteristics that fundamentally impact communication systems. These include tri-polarization, evanescent waves, beam splitting, beam focusing, spatial SnS, and various other distinctive physical properties.

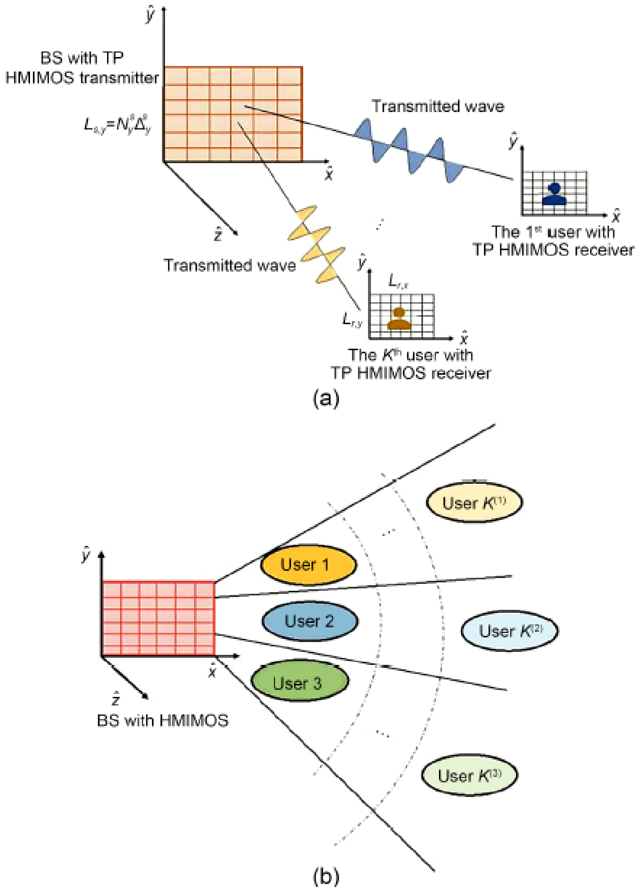


Fig. 3 Near-field multi-polarized spherical wave model

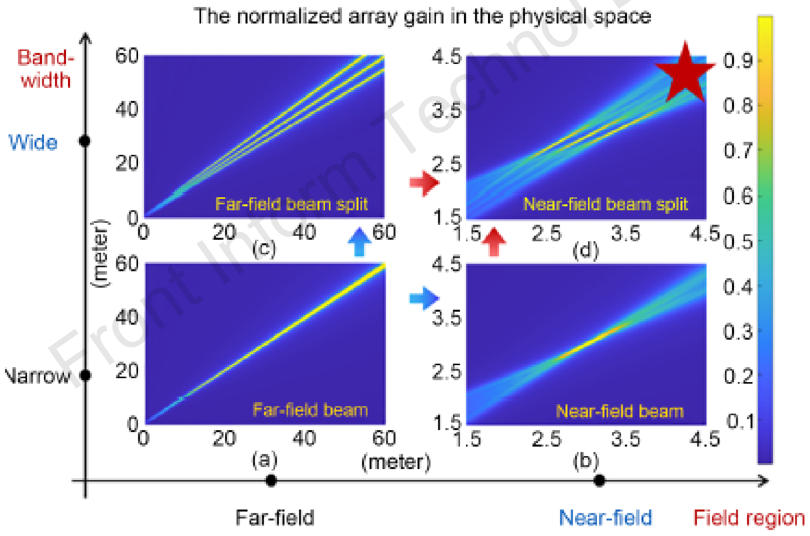


Fig. 4 Near-field beam-splitting effect schematic

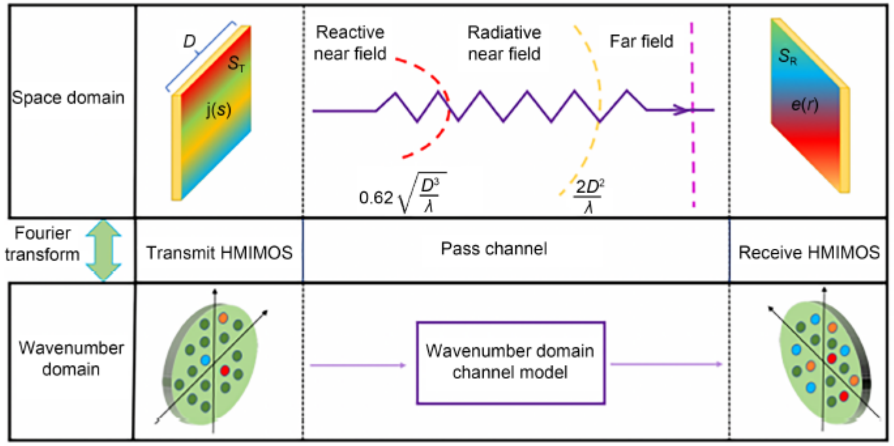


Fig. 12 Fourier plane-wave expansion channel model

CSI acquisition for near-field communications

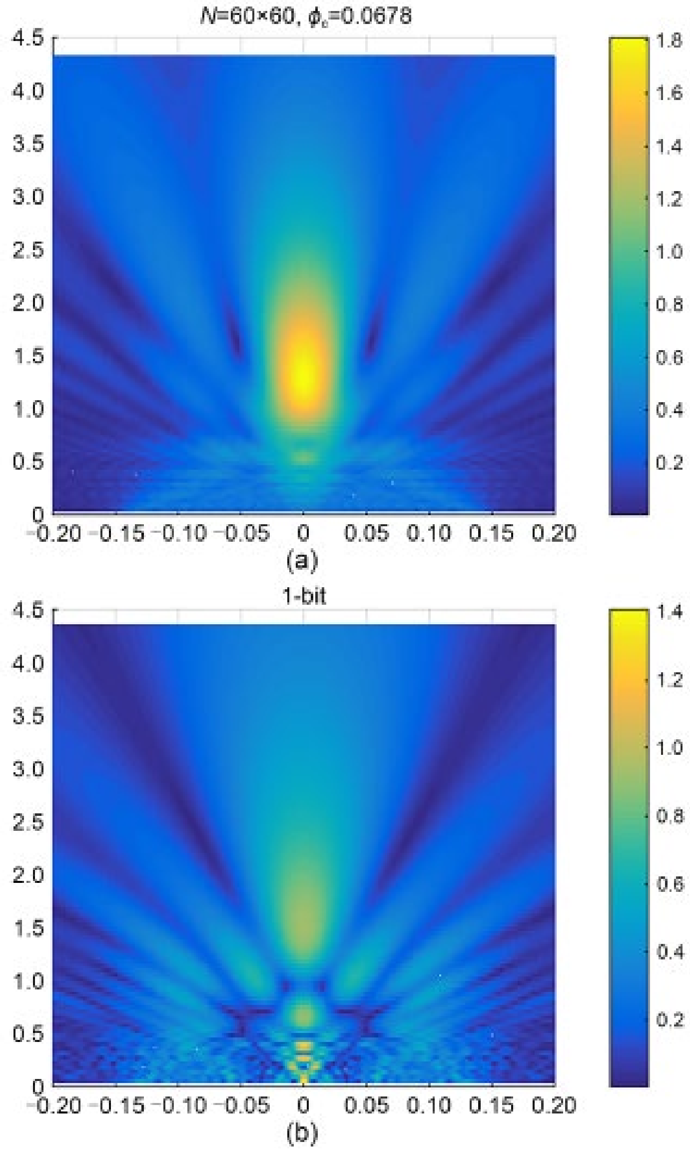
- Channel estimation
  - Challenges in CSI acquisition:
    - First, near-field MIMO systems typically incorporate a large number of antenna elements, significantly increasing the dimensionality of the channel to be estimated.
    - Secondly, the far-field Fraunhofer approximation is no longer valid for modeling near-field MIMO channels, requiring the adoption of more sophisticated spherical wave models.
  - Methods:
    - Compressed sensing based methods
    - DL-based methods: data-driven and model-driven
- Beam training:
  - Two-stage beam training scheme
  - Multi-user simultaneous beam training scheme

- Codebook design
  - The codebook is desiged which considers the propagation properties of both near-field spherical waves and far-field plane waves.

Fig. 22 Codebook-based near–far-field communications

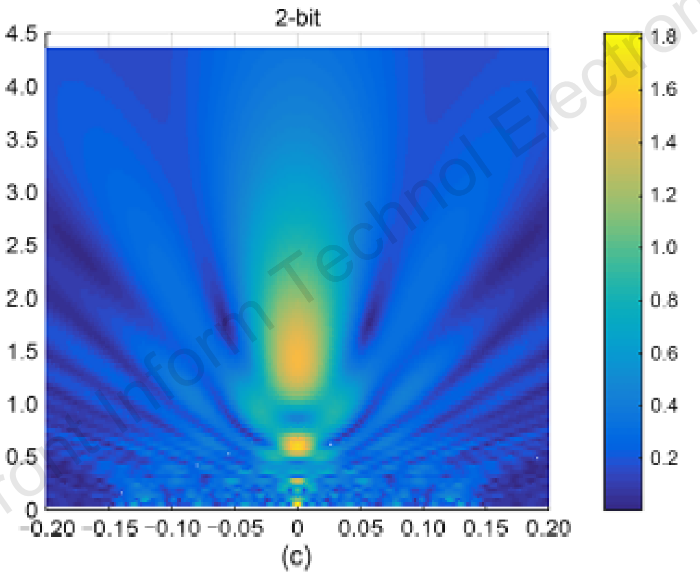
Near-field beams

- Non-diffractive beams: Near-field-enabled Bessel beams; Airy beams



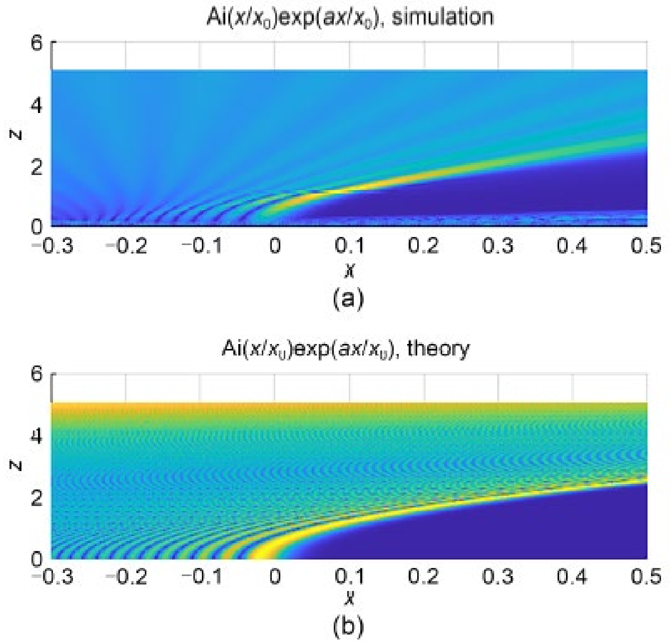
(a)

(b)



(c)

Fig. 24 Bessel beam intensity distribution and the impact of quantization: (a) Bessel beam; (b) 1-bit Bessel beam; (c) 2-bit Bessel beam



(a)

(b)

Fig. 25 Airy beams based on simulation (a) and theory (b)

Near-field beams

- Near-field-enabled OAM beams
  - In the near-field applications, vortex waves can be combined with non-diffractive beams, such as Bessel, Airy, Pearcy, and other special beams featuring unique properties.

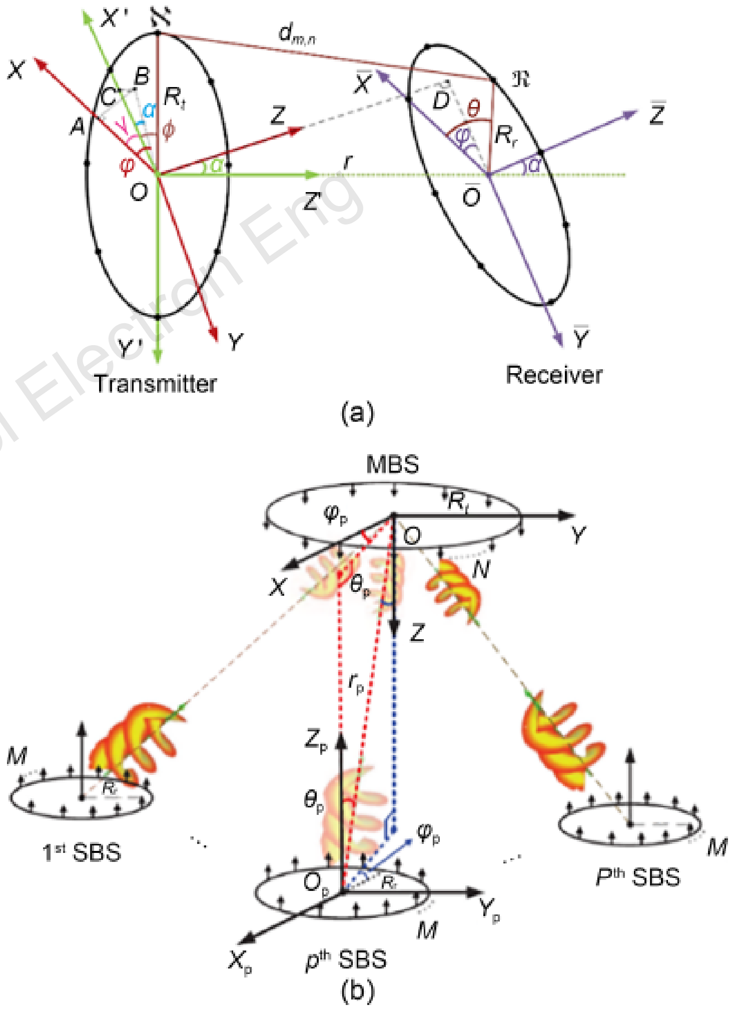
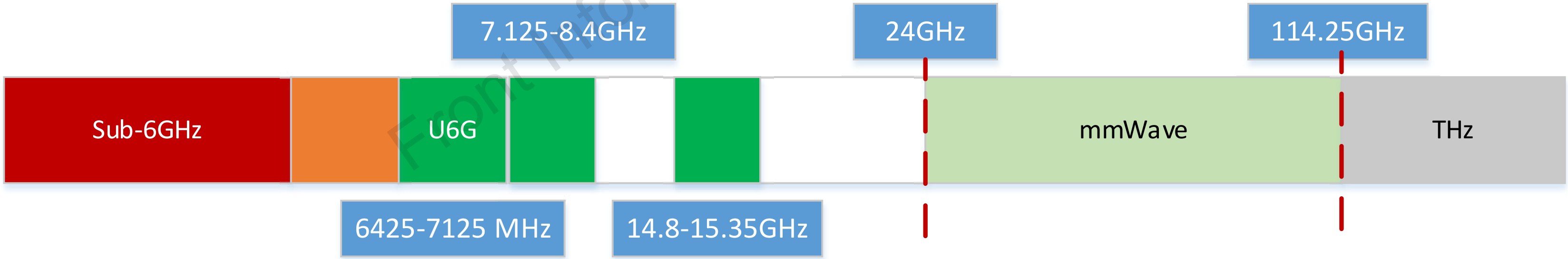


Fig. 27 UCA-based point-to-point and point-to-multipoint OAM transmission structure

Primary bands for 6G networks

- Several newly allocated frequency bands above 6 GHz are expected to serve as primary bands for 6G networks,
  - U6G (6 GHz upper band, i.e., 6425–7125 MHz)
  - upper mid-bands (7–24 GHz)
  - mmWave, and
  - even sub-THz bands
- These bands offer wide bandwidth and favorable propagation characteristics, making them well-suited to meet the demands of future cellular networks.

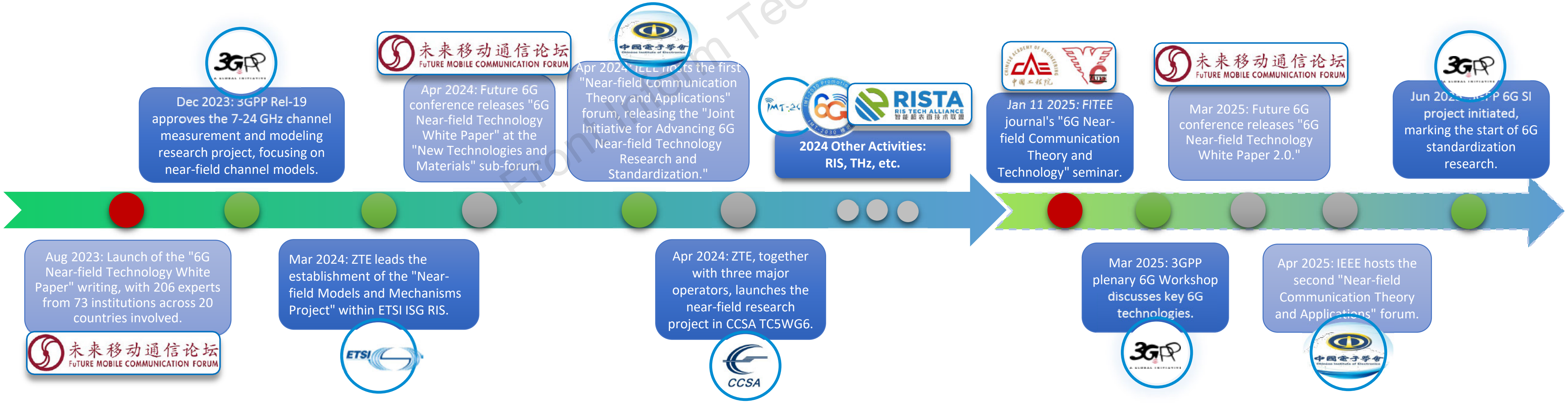


Enabling technologies and network deployment

- Challenges in constructing ubiquitous near-field propagation environments
  - Rayleigh distance vs. effective Rayleigh distance
  - Near-field distance in off-axis regions
- Enabling technologies
  - New types of APAA, including RIS-based phased array antennas, sparse array structures for phased arrays, and movable antennas
  - Cell-free massive MIMO is essential for enabling ubiquitous near-field propagation in future networks.
  - Reconfigurable intelligent surfaces (RIS): Compared to traditional APAAs, RISs offer passive regulation, low cost, and easy deployment, enabling dense and widespread deployment. This makes RISs a promising technology for creating a ubiquitous near-field channel environment for future 6G networks.
- Network deployment
  - Challenges of integrated communication–sensing–energizing networks
    - The distribution of these services varies.
    - The ideal propagation channel differs for each service.
    - Designing integrated waveforms for communication, sensing, and energy transfer poses a challenge.
  - In near-field assumption-based network deployment, the optimization objective must consider not only signal strength distribution but also the changes in spatial freedom caused by near-field propagation characteristics.

Standardization efforts

- Standardization research and protocol design
  - Near-field channel modeling
  - Near-field communication protocol design
    - General standard protocol design for near-field technology
    - Optimized standard protocol design with 6G key technologies
- Since 2023, academia and industry have closely collaborated to accelerate the in-depth research and standardization of 6G near-field technologies, aiming to facilitate the effective implementation of near-field technology in the upcoming 3GPP 6G international standards.



Aug 2023: Launch of the "6G Near-field Technology White Paper" writing, with 206 experts from 73 institutions across 20 countries involved.

Dec 2023: 3GPP Rel-19 approves the 7-24 GHz channel measurement and modeling research project, focusing on near-field channel models.

Mar 2024: ZTE leads the establishment of the "Near-field Models and Mechanisms Project" within ETSI ISG RIS.

Apr 2024: Future 6G conference releases "6G Near-field Technology White Paper" at the "New Technologies and Materials" sub-forum.

Apr 2024: IEEE hosts the first "Near-field Communication Theory and Applications" forum, releasing the "Joint Initiative for Advancing 6G Near-field Technology Research and Standardization."

Apr 2024: ZTE, together with three major operators, launches the near-field research project in CCSA TC5WG6.

2024 Other Activities: RIS, THz, etc.

Jan 11 2025: FITEE journal's "6G Near-field Communication Theory and Technology" seminar.

Mar 2025: 3GPP plenary 6G Workshop discusses key 6G technologies.

Mar 2025: Future 6G conference releases "6G Near-field Technology White Paper 2.0."

Apr 2025: IEEE hosts the second "Near-field Communication Theory and Applications" forum.

Jun 2025: 3GPP 6G SI project initiated, marking the start of 6G standardization research.

Future trends and challenges

Distributed transmission from a near-field perspective

- In distributed MIMO systems, APs that spread across different regions can be treated as part of a large and sparse array, making it feasible to apply the near-field theory to distributed transmissions.
- Investigate near-field theory for randomly positioned antennas to reduce feedback overhead, improve beamforming, and enhance distributed MIMO efficiency.

Tri-polarization transmission in the near field

- In the context of XL-array in the near field, an additional polarization axis can be exploited to use the EM spectrum more efficiently, resulting in higher data rates and improved spectral efficiency.
- The practical application of near-field tri-polarization transmission requires careful consideration of user placement and system design to achieve the optimal performance.

Mobility in the near field

- Near-field propagation conditions present more significant mobility challenges: (1) Beam's focal spot is smaller; (2) The spatial DoFs vary significantly depending on the distance and angle relative to the antenna aperture; (3) Mobility may cause beam misalignment. Additionally, sensing tasks may lose track of targets due to mobility.

Sensing in the near field

- Design of low-complexity sensing algorithms
- Design of the sensing algorithm with multicarrier waveforms

WPT in the near field

- In 6G near-field scenarios, focused RF energy beams improve transfer efficiency by directing energy to receivers.

Conclusions

- **Overview of Near-field Technology:** The paper provides a comprehensive review of recent advancements in the near-field technology and its role in enhancing 6G communication systems.
- **Near-field Propagation:** Covers key aspects, such as definitions, transmission properties, and performance metrics.
- **Channel Models:** Discusses deterministic, stochastic, and EM information theory-based models for near-field channels.
- **Redesigning Traditional Mechanisms:** Emphasizes the need to optimize channel estimation, beam training, and codebook design to align with near-field characteristics.
- **Innovative Beam Designs:** Introduces non-diffractive beams (e.g., Bessel and Airy) and OAM beams, which hold promising potential for breakthroughs in near-field communication.
- **Engineering and Standardization:** Highlights advancements in engineering and standardization, including the 6G spectrum and enabling technologies.
- **Research Directions:** Suggests promising future research areas that could significantly impact system design.
- The review underscores the critical role of near-field technologies in advancing 6G and future communication systems, serving as a valuable resource for researchers and practitioners.

Yajun ZHAO holds Bachelor’s, Master’s, and Doctoral degrees. Since 2010, he has served as Chief Engineer at the Wireless and Computing Product R&D Institute of ZTE Corporation. Previously, he worked in wireless technology research at Huawei Wireless Research Department. His current work focuses on 5G standardization and the 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, Yajun ZHAO holds more than 200 granted patents related to 4G LTE and 5G NR mobile communication technologies, with over 20 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). Linglong DAI has received numerous awards, including six IEEE conference Best Paper Awards at IEEE ICC/GLOBECOM/VTC, the Electronics Letters Best Paper Award in 2016, the Outstanding Young Scholar of NSFC in 2017, the IEEE ComSoc Asia–Pacific Outstanding Young Researcher Award in 2017, the IEEE ComSoc Leonard G. Abraham Prize in 2020, the IEEE ComSoc Stephen O. Rice Prize in 2022, and the Distinguished Young Scholar of NSFC in 2023. In addition, he was named an IEEE Fellow in 2021 and received the IEEE ICC Outstanding Demo Award in 2022. 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, Deputy Director of the State Key Laboratory of Networking and Switching Technology, and 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 published five books and three book chapters, and has been granted over 70 patents, receiving distinctions such as the Chinese Patent Excellence Awards and a gold medal at the Geneva International Exhibition of Inventions. She is a recipient of the Young Female Scientist Award. She serves as the Executive Associate Editor of *Frontiers of Information Technology & Electronic Engineering*, an Associate Editor *of IEEE Transactions on Antennas and Propagation*, and the Executive Editor-in-Chief of special issue of *Engineering*. In addition, she is the Lead Guest Editor for special issue of *IEEE Antennas and Wireless Propagation Letters*. Previously, she served as an Associate Editor for *IEEE Wireless Communications Letters* and as Lead Guest Editor for special issue of *IEEE Communications Magazine*. 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, Jianhua ZHANG 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, AI-enabled channel prediction, digital twins, and testing technologies.

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