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Mobile near-field terahertz communications for 6G and 7G networks: Research challenges

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Following the current development of the wireless technology landscape, and with respect to the constant growth in user demands, it is inevitable that next-generation mobile wireless networks will use new frequency bands located in the sub-terahertz and terahertz (THz) spectrum to complement the existing microwave and millimeter wave (mmWave) channels. The feasibility of point-to-point stationary THz communication links has already been experimentally demonstrated. To build upon this breakthrough, one of the pressing research targets is making THz communication systems truly mobile. Achieving this target is especially complicated because mobile THz wireless systems (including WLANs and even cellular access) will often operate in the near-field due to the very large (even though physically small) electrical size of the high-gain antenna systems required for making high-rate communication links feasible at such frequencies. This perspective article presents several key prospective research challenges envisioned on the way to designing efficient mobile near-field THz wireless access as a part of 6G and 7G wireless landscapes.

KEYWORDS

next-generation networks, THz, Bessel beams, Airy beams, orbital angular momentum, OAM, beamfocusing, mobility

1 Introduction

The research community's disposition towards terahertz (THz) wireless communications has notably evolved over recent years. The THz band is broadly defined as the range from 0.1 THz to 10 THz with 0.1 THz—0.3 THz often referred to as *sub-THz*, 0.3 THz–1 THz sometimes referred to as *lower THz*, and 1 THz–10 THz referred to as either *higher THz* or *true THz* (Piesiewicz et al., 2007; Alliance, 2022; Petrov et al., 2020a; Sen et al., 2020). While the phenomenon of THz radiation has long been exploited for imaging and sensing (Rappaport et al., 2019), using the THz band for communications was not widely explored until the 21st century (Elayan et al., 2020; Akyildiz et al., 2022). Within the past two decades, the general opinion on using THz signals for data transmission has evolved from considering such proposals as science fiction to the recent understanding that THz or, strictly speaking, sub-THz wireless is likely to complement state-of-the-art microwave and millimeter wave (mmWave) systems in 6G (Samsung, 2020; Nokia, 2022).

The first standardization effort regarding the (sub-)THz wireless connectivity has already been established (IEEE, 2017), and now the work continues to extend the range up to ≈ 450 GHz (Iwao Hosako, 2022). THz communication systems themselves have also developed significantly over the last 20 years. Namely, the maximum output power of THz devices has increased substantially to enable experimental demonstrations of long-range point-to-point THz links (Castro et al., 2020; Sen et al., 2022). Such advances make point-to-point wireless links over (sub-)

THz bands practical in the foreseeable future. As these links continue to improve, we believe that it is the right time for the research community to slowly shift its focus toward exploring **mobile** THz communications that can be used for cellular, wireless local area networks (WLANs), on-body radio links, or similar scenarios. Here, there are numerous open challenges to be solved, including but not limited to: beam steering, node discovery, directional channel access, and efficient multiple access.

There is also a seemingly hidden point of consideration within these challenges: **while existing mobile microwave and mmWave data links almost always work in the far-field, mobile THz wireless communications for WLANs and cellular access will often have to operate in the THz near-field**. Although near-field communications are not fundamentally new, efficiently exploiting near-field propagation when designing (i) mobile (ii) tens of Gbps and even Tbps (iii) extremely-directional communication solutions which operate at (iv) THz frequencies is a broad and challenging research area. Many of the design approaches, conclusions, and even theoretical boundaries extrapolated from the microwave and mmWave communications must be revisited, as a fundamental cornerstone of such studies (Zhao, 2019), i.e., the far-field assumption (Balanis, 2015), is not applicable for THz applications.

This article presents the authors' perspective on exploring this attractive research topic of enabling mobile near-field THz communications. First, in Section 2, we elaborate on why mobile THz links will often be near-field and why this fact cannot be ignored in the design of prospective communication systems. Then, Section 3 outlines the major challenges in deriving the necessary theoretical models. Section 4 discusses the engineering challenges in effectively utilizing the findings from Section 3 for a mobile THz system design in the near field. Finally, Section 5 concludes the paper advocating mobile near field THz communications as an essential element of late 6G or, more likely, 7G wireless systems.

2 THz near field—A likely scenario in mobile THz communications

Recall that, when an electromagnetic (EM) signal is generated from an antenna or antenna array, its propagation characteristics depend on the electric field distribution across the radiating aperture (Balanis, 2015). Thus, by considering an aperture to be a collection of infinitely small isotropic radiators, the total electric field strength can be evaluated by the superposition principle—where the amplitudes and phases of these small radiators can be manipulated for a desired radiation profile. The radiating region consists of two main parts: the near field and the far field. The boundary between these fields is given by the Fraunhofer distance $d_F = 2D^2/\lambda$, where λ is the signal's wavelength, and D is the largest dimension of the antenna aperture (Balanis, 2015).

What is new with THz?: Currently, for a typical WLAN access point (AP) D is approximately 10 cm. Keeping a sub-THz AP the same size but using a carrier frequency of 300 GHz, the far-field would start at 20 m. Applying the same logic to cellular-type APs operating at 1 THz with array dimensions up to 25 cm, the far field would begin 400 m away from the transmitter. *Hence, many use cases for prospective (sub-)THz communications will operate in the near field, as illustrated in* Figure 1.

One may argue that there is no need for the physical size of these devices to be so large and that by using smaller devices the near-field region can be minimized. Indeed, there exist THz horn antennas with gains of over 25 dBi and physical sizes of a few millimeters, so the near-field propagation lasts for no more than 5 cm (Diods, 2019). These types of antennas can be applied to **short-range, idealistic, and stationary** line-of-sight THz links with perfect alignment of antennas.

In contrast, much higher gains (and consequently larger antenna systems) are needed to provide reliable connectivity for **realistic mobile** THz communications. In addition, in mobile scenarios, efficient horn antennas should be replaced with electronically-steerable THz arrays or reconfigurable intelligent surfaces (RISs), since it is often impractical to mechanically steer a THz horn antenna following multiple mobile nodes. The antenna array size at the THz AP must be large enough to account for many unwanted effects, including but not limited to more noise captured in larger bandwidths, imperfect beam alignment, non-negligible noise figure at the THz receiver, and potentially non-line-of-sight communications. Therefore, we argue that prospective mobile sub-THz, and especially THz communications will have a sizable near-field zone, and its peculiarities must be accounted for in both system design and performance evaluation.

Why cannot the THz near-field be ignored?: First, in the far field, the entire antenna or array aperture can be considered a single source, which generates a beam with a given direction and width; the beam spreads out as it propagates. These assumptions do not hold in the near field, and the radiation profile of the signal becomes important (Balanis, 2015). Second, beamforming is "focusing" at infinity, thus the extremely narrow *"pencil-sharp"* beam generated in the far field of a large-scale THz array (Monroe et al., 2022) is substantially wider in the near field. Thus, canonical far-field beamforming is less efficient in the THz near field (Singh et al., 2022).

3 Research challenges: Theory and modeling

In this section, we discuss the challenges related to modeling the THz near field, as the phenomenon must be better understood before efficient mobile solutions can be developed. These challenges and the engineering decisions they demand (discussed in Section 4) are illustrated in Figure 2.

3.1 Challenge 1: Near-field THz channel modeling

Several previously proposed (sub-) THz channel models (Lin and Li, 2015; Han and Akyildiz, 2016; Sarieddeen et al., 2019; Wang et al., 2021), assume canonical beamforming and/or far-field propagation. If these channel models address the near-field region, they generally focus on the spherical wave model, which is the simplest approximation of near-field propagation of an equivalent far-field plane wave. Thus, the fundamentals of THz channel modeling must be revisited, this time accounting for customized and optimized near-field propagation.

Near-field propagation can be well described using the applicable Maxwell's equations, which present a set of coupled partial differential equations explaining the interrelation of electric and magnetic fields. The set can be solved numerically for every point in the environment as the EM wave propagates. However, this fundamental numerical approach is

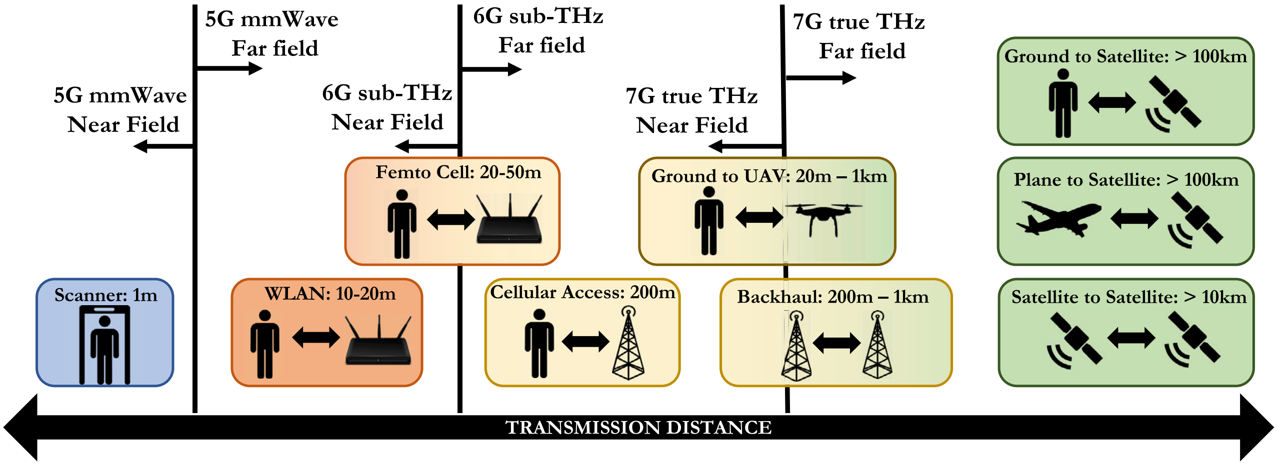

FIGURE 1
Expansion of near-field use cases from 5G through 6G to 7G networks.

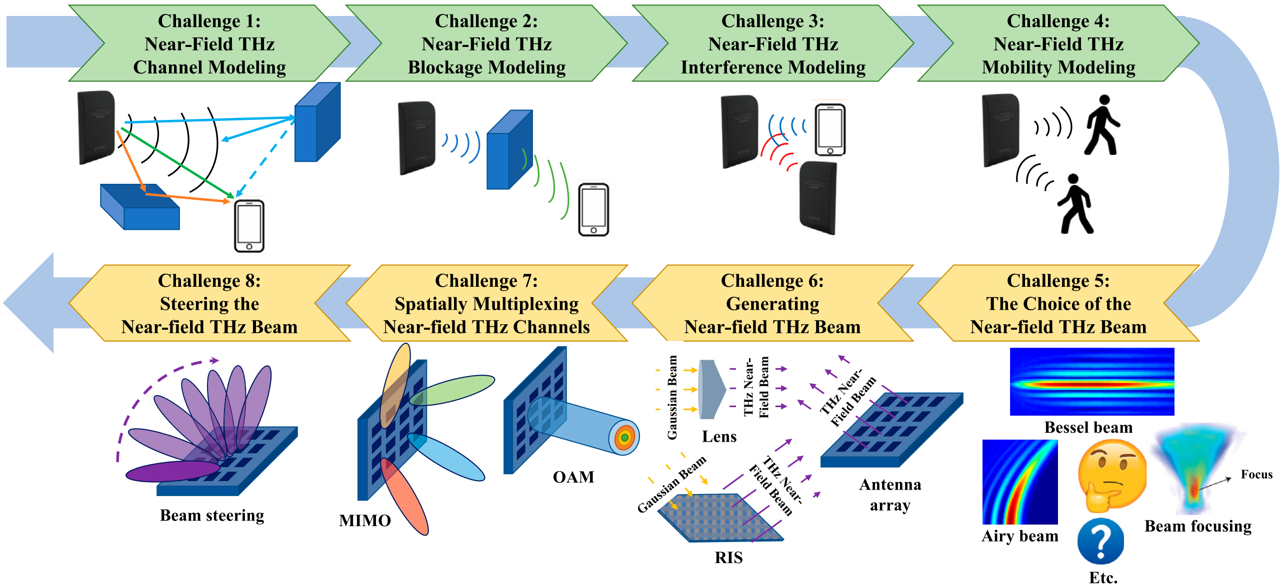

FIGURE 2
Key research challenges to enable 7G-grade mobile near-field THz wireless networks.

impractical in many setups due to its extensive computational complexity (Balanis, 2015). Therefore, the first research challenge for mobile near-field THz systems is finding a channel model accurate enough to represent all the major effects of THz near-field propagation and simple enough to be used further in other studies.

One way to approach this challenge is by first finding an approximation for the line-of-sight scenario. Then, the model can be enhanced to account for: (i) beam steering; (ii) signal reflection; and (iii) signal scattering from the obstacles. Later, the developed models may be tailored to scenario-specific deployments (i.e., indoor, outdoor, and vehicular setups). It is also important to account for the potential asymmetry of the THz channel. For example, if a mobile is being serviced by a THz AP equiped with a large antenna system, the AP may be in the THz far field of the mobile node while the mobile node is in the near field of the AP. Finally, these extensions may be combined into a stochastic channel model for near-field THz links [i.e., by extending existing 3GPP mmWave models (3GPP, 2022)].

3.2 Challenge 2: Near-field THz blockage modeling

While the previous challenge focuses on homogenous environments, the phenomenon of the THz signal propagation *through* an obstacle when still in the near field deserves specific attention. Prior studies, including (Kokkoniemi et al., 2016; Petrov et al., 2017; Eckhardt et al., 2021; Wu et al., 2021), did not emphasize the differences between blockage in the far field vs. the near field. Hence, these findings and conclusions must be revisited, and additional measurements and modeling efforts targeting the THz signal penetration losses in the near field are needed. The modeling and measurements should start with typical indoor and outdoor materials/objects, including walls (concrete, steel, wood, *etc.*), windows (glass), and furniture (wood, steel, aluminum, plastic, *etc.*) with the distances up to tens/few hundreds of meters for outdoor setups (Akyildiz et al., 2022). This knowledge can later be incorporated into the corresponding THz near-field channel models discussed above.

3.3 Challenge 3: Near-field THz interference modeling

The third large research task here is to extend the point-to-point models from Challenge 1 and 2 to a multi-node network, where interference among concurrent transmissions may be non-negligible. While prior studies on directional mmWave and THz communications reveal that interference from pencil-sharp beams is rarely an issue (Venugopal et al., 2016; Petrov et al., 2017), THz beams have a different structure in the near field, so the earlier analyses are not directly applicable. Moreover, novel channel models from Challenge 1 may lead to notable differences in a multi-node setup. Therefore developing appropriate interference models for near-field THz systems is an important research challenge.

We suggest the study apply a conventional bottom-up approach, starting with a simple 2D scenario, as in (Petrov et al., 2017). Then, the model can be extended to a 3D case, considering nodes at different heights, and tailored to scenario-specific deployments (WLANs, intra-cell/inter-cell interference).

3.4 Challenge 4: Near-field THz mobility modeling

The mobility of devices may also impact the near-field propagation. As we hope to keep THz transmissions highly directional in the near field, both conventional large-scale mobility (i.e., pedestrian or vehicular), as well as small-scale mobility (i.e., node displacements or rotations) (Petrov et al., 2018; Petrov et al., 2020b; Kokkoniemi et al., 2020) should be considered. These movements will challenge the reliability of the device's THz link and the performance of the THz network by creating unpredictable interference to other transmissions. Studies measuring mobility patterns should be combined with the new propagation characteristics from Challenges 1 through 3 to correctly estimate the new impact of mobility patterns in mobile near-field THz networks. An additional important research question here is a node's mobility between the THz near-field and far-field zones, which in turn could impact the optimal type of THz beam (examples of which are detailed in the next section). Furthermore, the potential co-existence of THz near-field users and THz far-field users in the same cell needs to be explored.

4 Research challenges: Engineering near-field solutions

4.1 Challenge 5: The choice of the near-field THz beam

State-of-the-art far-field beamforming has notably lower efficiency in the near field (Balanis, 2015; Dovelos et al., 2021; Singh et al., 2022). Thus, alternative solutions should be considered to achieve high-gain links in the near field. One option is *beamfocusing*: the beam is focused at a spot a certain distance from the transmitter. Beamfocusing, however, has inherent limitations in mobile environments because it demands perfect estimation of the transmission distance and continuous re-focusing when it changes (Dovelos et al., 2021). Therefore, other solutions have recently received attention, most notably, using wavefront engineering to generate non-Gaussian beams.

Although Gaussian beams have long been the default for communications, other beams may present benefits in the THz near field. Bessel beams (Durnin, 1987), for example, are non-diffracting with a greater depth of focus than Gaussian beams and self-healing properties that potentially reduce the blockage problem for near-field communications (Vetter et al., 2019). Cosine-Gauss beams are the one-dimensional counterparts of Bessel beams and have the same properties in one dimension (Lin et al., 2012). Airy beams are curved which can provide an alternative approach to blockage mitigation (Siviloglou et al., 2007) or can change the angle of incidence to improve beam alignment. There are other possible options, and the beam design parameters may depend heavily on the application. Thus, selecting the most appropriate beam(s) for mobile near-field THz communications is an open research problem with many candidate solutions.

4.2 Challenge 6: Generation of the THz near-field beam

There are three primary ways to generate a non-Gaussian beam (Headland et al., 2018): (i) passing a Gaussian beam through a dielectric lens to impart a phase transformation (Arlt and Dholakia, 2000); (ii) using an antenna array to control the phases of the radiating elements and generate the wavefront of the desired beam; and (iii) using an RIS to impart the desired phase transformation before reflecting or transmitting the beam towards the receiver (Zhu et al., 2017; Dovelos et al., 2021; Singh et al., 2022).

Considering these options, the key metrics are the accuracy of phase control, reconfigurability, and device complexity. While custom-printed lenses provide the maximum phase accuracy, they cannot be repurposed for mobile links. Antenna arrays enable flexibility through electrical manipulation of the radiating elements but at the cost of complexity. RISs allow for flexibility and reduced complexity, but utilize discretized phase shifters which lead to lower accuracy. Furthermore, many of these approaches to beam generation will suffer *the beam squint effect* - since the same phase delay translates to different time delays for different frequencies, there can be imperfections in the generated beam when using phase shifters on a broadband signal. One possible solution is to use true-time-delay (TTD) lines (Frigyes and Seeds, 1995), but they are significantly more complex and cannot be easily repurposed for the THz regime. Hence, designing an efficient system able to generate and manipulate the desired beam is an important challenge.

4.3 Challenge 7: Achieving spatially multiplexed channels for mobile links

The near-field regime in 6G and 7G scenarios is challenged further by the fact that the (sub-)THz spectrum is unlikely to offer continuous bands of many hundreds of GHz, as many sub-bands in sub-THz frequencies (up to 275 GHz) are already occupied by essential services, such as radars, sensors, and Earth exploration satellites (Polese et al., 2022). To stay within reasonable bandwidths (realistically, tens of GHz) while achieving the expected rate of Tbps (Huang and Wang, 2011), spatially multiplexed channels (Akyildiz and Jornet, 2016) are necessary. Here, conventional multiple-input multiple-output (MIMO) is challenged due to a strong line-of-sight bias of THz-band communication links, as well as near-perfect CSI requirement (Maletic et al., 2021). In addition, generating spatially separate channels with pencil-thin beams is severely complicated in the near field.

An interesting opportunity is to utilize orbital angular momentum (OAM) for orthogonal mode division multiplexing (MDM) (Yan et al., 2014; Ren et al., 2017; Zhou et al., 2022), ideal for line-of-sight scenarios. MDM provides the same increase in capacity as perfect, uncorrelated MIMO for the same array size (Oldoni et al., 2015), with significantly reduced signal processing components (Zhang et al., 2016). Further, OAM is naturally present in several beam options in Challenge 5 (Arlt and Dholakia, 2000). The challenge, however, lies in capturing enough of the wavefront to correctly decode the OAM modes, which increases the demands on receiver size and positioning, especially as the number of OAM modes increases (Trichili et al., 2016; Yu et al., 2016; Zhu et al., 2017). Therefore, engineering the best way to spatially multiplex channels in the THz near-field is an important research challenge.

4.4 Challenge 8: Steering the THz near-field beams

The ability to electronically steer beams toward the receiver is a mandatory feature to make THz communications truly mobile. The Huygens-Fresnel principle, which is used to derive the required phase configuration for a particular wavefront, gets more complicated as the angle of deviation from the transverse direction of propagation increases (Headland et al., 2018). Thus, when mobile links require beams to be steered farther from the broadside, it is more difficult to derive the necessary phases accurately, and the generated beam may exhibit sidelobes or other unintended effects (Balanis, 2015). Powerful processing methods might be able to model such situations, but real-time implementations would be limited by the signal processing resources of the system; it may simply be unsustainable to design custom beams with significant deviations from the broadside.

However, given that the effective aperture of an antenna array reduces as the propagation direction deviates from the broadside, the far-field distance reduces, and canonical beamsteering (with reduced gain) becomes more viable. Therefore, one possible solution might be a hybrid approach using a non-Gaussian beam for smaller steering angles and classical beamforming for angles farther from the transverse direction. Still, a more efficient approach is desired, presenting another research challenge toward true mobile near-field THz communications.

5 Conclusion and the road ahead

With 5G mmWave systems in their deployment stage and 6G networks around the corner, we advocate that one of the important research directions for the next decade(s) will be related to designing and developing *efficient mobile near-field THz communications*. We present our perspective on the key research challenges associated with these systems as well as potential new opportunities that come alongside them. The presented set is not exhaustive, and we envision other challenges and opportunities (in security, joint communications and sensing, and coverage extension, among others) to emerge as the main ones summarized in the article are explored. We strongly believe that efficient harnessing of mobile near-field THz communications will provide a non-incremental contribution to the wireless technology landscape thus bringing the performance of corresponding 6G-grade and 7G-grade networks to a new level.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

VP, DB, and AS contributed to developing and presenting the underlying study. All authors contributed to manuscript preparation, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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