MOBILE TERAHERTZ COMMUNICATION AND SENSING SYSTEMS

A Future Look

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As we move into an era of unprecedented connectivity, the potential of terahertz (THz) mobile communication is emerging as a key driver of the next technological revolution [1]. Positioned between the microwave and infrared regions of the electromagnetic (EM) spectrum, the THz frequency band (0.1–10 THz) offers vast bandwidths, which, when properly utilized, can open the door to ultrafast data transfers exceeding terabits per second. At the 2019 World Radiocommunications Conference, 137 GHz of spectrum were identified for the use of terrestrial THz communications in the frequency range between 275 GHz and 450 GHz [2]. A complete inventory on the regulatory situation above 100 GHz has been recently provided by the European Telecommunications Standards Institute (ETSI) [3].

Introduction

Over the past years, the "THz technology gap," named for the lack of functional devices in this frequency range, has steadily narrowed due to significant advances in electronic, photonic, and plasmonic technologies. Consequently, experimental work and system-level demonstrations have emerged to support new use cases and connection demands. These solutions are no longer mere adaptations of lower-frequency techniques but are instead designed to harness the unique potential of THz devices and address the specific challenges of the THz channel.

From the Internet of Nano-Bio Things to space communication, the THz frequency range is set to unlock opportunities across different scales (see Figure 1). On the one hand, the very small wavelength of THz signals (from 3 mm down to 30 μm) allows the development of extremely small antennas, embeddable everywhere. On the other hand, for a fixed footprint, THz antennas can provide much higher gains than gigahertz antennas. The resulting directivity of THz systems not only enables them to achieve adequate communication range but also minimizes interference between devices. As a result, next-generation wireless technologies beyond 5G are

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expected to leverage THz waves to achieve key performance indicators, ranging from peak data rates of at least 1 Tbps to a connectivity density of up to 10^7 devices per square kilometer [4]. Such service requirements position mobile THz links as a key area of research to complement the established stationary THz links. A clear indication of the growing interest and rapid advancements in THz mobile communication is the increasing number of publications on this topic, as shown in Figure 2. This surge not only underscores the importance of this technology but also highlights the need for a comprehensive exploration of its future potential.

As such, there is a growing demand for visionary insights into how this technology will evolve in the coming years. Terahertz mobile communication extends beyond merely enhancing existing networks; it promises to unlock new dimensions of interaction. This article provides a forward-looking perspective on the long-term implications and applications of THz mobile communication. We identify the convergence of electronics and photonics components, as well as analog and digital signal processing techniques, as essential to realize the full potential of THz frequencies (see the "Convergence in Terahertz Technologies" section). Integrated sensing and communication (ISAC) will be foundational for achieving seamless connectivity in future networks (see the "Mobile ISAC" section). In addition, wavefront engineering is expected to revolutionize how we manipulate EM waves, further enhancing the capabilities of THz communication (see the "Dynamic Beam Shaping and Wavefront Engineering" section). We also examine potential applications from diverse perspectives, exploring how they will evolve as the technological foundations of THz mobile communication mature (see the "Prospective Applications" section). Our discussion goes beyond traditional mobile and wireless networks and includes two extremes on scales: THz mobile communication at the nanoscale and next-generation satellite and space networks in the terahertz band (see the "Terahertz Systems to the Extremes" section). By focusing on these pivotal areas, we aim to chart a path for the future of THz mobile communication, offering solutions that will shape the technological landscape in the years to come (Table 1).

CONVERGENCE *IS THE KEYWORD, BOTH WHEN IT COMES TO THE MERGER OF ELECTRONIC AND PHOTONICS TECHNOLOGIES, AS WELL AS ANALOG AND DIGITAL SIGNAL PROCESSING TECHNIQUES.*

Convergence in Terahertz Technologies

Terahertz technology has drastically evolved in the last two decades. Today, state-of-the-art terahertz radios can deliver around 200 mW of power at 100- to 300-GHz frequencies [5]. This power is comparable to that of a Wi-Fi 7 device or a 5G cellphone in the sub-6-GHz range. Of course, the efficiency of a THz radio (≤20%) is still far from sub-6-GHz radios (50%–80%). Nevertheless, in the same footprint of a microwave antenna (e.g., more than 6 cm for a half wavelength dipole at 2.4 GHz), one can build a directional terahertz antenna with high-gain (e.g., 20–30 dBi for a 6-cm antenna at 240 GHz). When such antennas are simultaneously used at the transmitter and the receiver, it is actually easier to close the link at THz frequencies than it is at microwave frequencies, provided that there are line-of-sight (LoS) or strong non-LoS paths

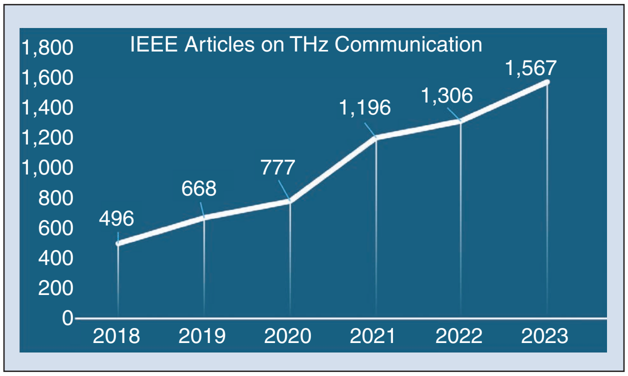

FIGURE 2 Publications on THz mobile communications issued in IEEE in recent years.

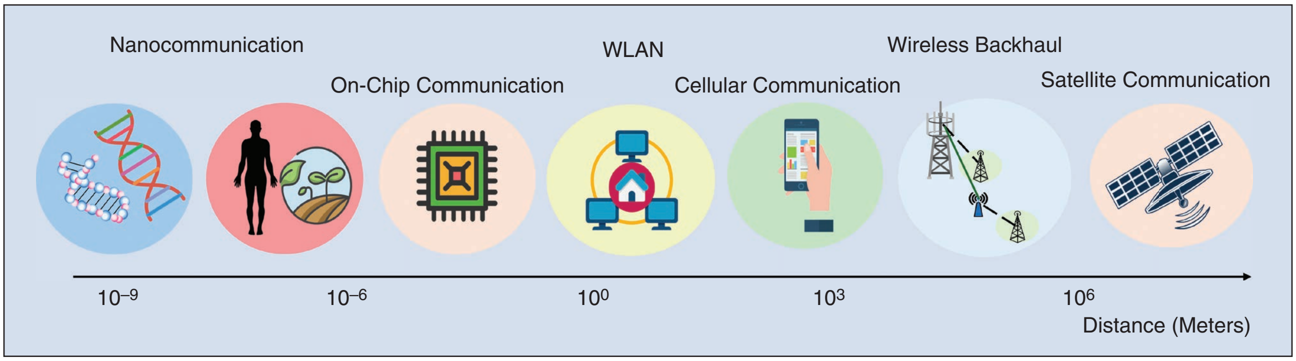

FIGURE 1 Terahertz applications across scales: from nanocommunication to satellite networks. WLAN: wireless local area network.

THE CONVERGENCE OF ELECTRONICS AND PHOTONICS BEGINS WITH INTEGRATING FIBER-OPTIC AND WIRELESS NETWORKS AND EFFECTIVELY COMBINING THESE COMPONENTS TO ENHANCE TRANSCEIVER PERFORMANCE.

(but we will also discuss in the "Dynamic Beam Shaping and Wavefront Engineering" section ways to overcome signal blockage). However, the challenges increase when supporting links with bandwidths that can easily span 10 GHz or more. The larger the bandwidth, the larger the noise at the receiver, and, ultimately, the signal-to-noise ratio is the factor that sets the achieved performance. Moreover, finding ways to efficiently process the signals at the transmitter and the receiver becomes more challenging as the bandwidth increases.

In this section, we discuss the next steps in the evolution of THz technologies. *Convergence* is the keyword, both when it comes to the merger of electronic and photonics technologies, as well as analog and digital signal processing techniques.

Electronics and Photonics Convergence

During the early 2000s, as the global development of THz wireless communication technology gained momentum; systems using photonic devices—such as laser light sources, optical modulators, and photodiodes—dominated research and development on the transmitter side. On the receiver side, electronic devices and integrated circuits were used, exemplifying the convergence of photonics and electronics. In the 2010s, THz semiconductor electronic device and integrated circuit technologies made significant progress [6]. Notably, all-electronic transceivers using compound semiconductors, such as gallium arsenide, indium phosphide, gallium nitride [7], as well as those based on silicon (Si)-based semiconductor devices like Si-CMOS and silicon-germanium heterojunction bipolar transistor, began to operate in the 300-GHz band, attracting global attention. By the 2020s, the need to seamlessly connect optical and wireless networks spurred research into effectively integrating transceiver technologies based on both electronics and photonics.

Figure 3 shows the key devices and components for both electronics-based and photonics-assisted transceiver technologies. For example, in photonics-assisted transceiver technology, it is necessary to improve the output and efficiency of photodiodes and enhance the performance of THz optical modulators. In electronics-based transceiver technology, transmission lines connecting the components are crucial, and ongoing research is expected to advance dielectric transmission lines and THz fibers as replacements for hollow metallic waveguides.

Figure 3 also predicts how applications will expand over the years as both transceiver technologies are combined. Not only will the performance of each of the mentioned devices and components improve, but it will also be necessary to integrate the required electronic and photonic devices onto the same chip, as is currently done with silicon photonics. In other words, in addition to advancements in digital silicon photonics, research and development of "radio-frequency silicon photonics" technology must be pursued vigorously.

The convergence of electronics and photonics begins with integrating fiber-optic and wireless networks and effectively combining these components to enhance transceiver performance. For instance, oscillators utilizing photonics technology offer superior performance in terms of phase noise, making them suitable for incorporation into fixed wireless systems and other applications. As integration advances, it is anticipated that size and cost barriers will be overcome, broadening the range of applications to include general purpose oscillators or clocks.

TABLE 1 Summary of key research challenges.

Topic	*Challenges*
Convergence in terahertz technologies	• Heterogeneous semiconductor materials and devices integration • Electronic-photonic systems integration • High-speed device interconnects • Massive 2D arrays • High-speed broadband analog and digital signal processing
Mobile ISAC	• Intense Doppler spread • Real-time broadband channel estimation • Ultrawideband modulation and coding • Time-critical and low-latency applications • Capabilities of monostatic base station sensing
Dynamic beam shaping and wavefront engineering	• Antenna size and directionality • Transition between near- and far-field regions • Practical wavefront generation in transmission and reflection • Nondiverging, self-healing, and curving beams manipulation • Dynamically reconfigurable electromagnetic surfaces

One of the most promising applications of miniaturization and integration is the phased array, which employs numerous antennas and transceivers. Most of the THz communication systems shown to date rely on high-gain directional antennas, including horn antennas (often combined with lenses) and Cassegrain antennas. In that case, only manual or mechanical pointing is possible, limiting their applicability in mobile systems. Instead, programmable antenna arrays are needed. For the time being, only a few sub-THz arrays have been demonstrated [8]. As frequency increases, antenna spacing becomes smaller than the chip size of each component or transceiver. A critical challenge is whether the antenna and transceiver can be effectively connected. THz interconnects using dielectric waveguides and optical interconnects may offer potential solutions. In the "Dynamic Beam Shaping and Wavefront Engineering" section, we will elaborate on the requirements and opportunities for antenna arrays, reflect arrays, and metasurfaces.

Moreover, ISAC systems, which combine sensing and communication and will be extensively discussed in the "Mobile ISAC" section, exemplify the convergence of photonics and electronics. For example, in-vehicle sensors that utilize both light and radio waves represent

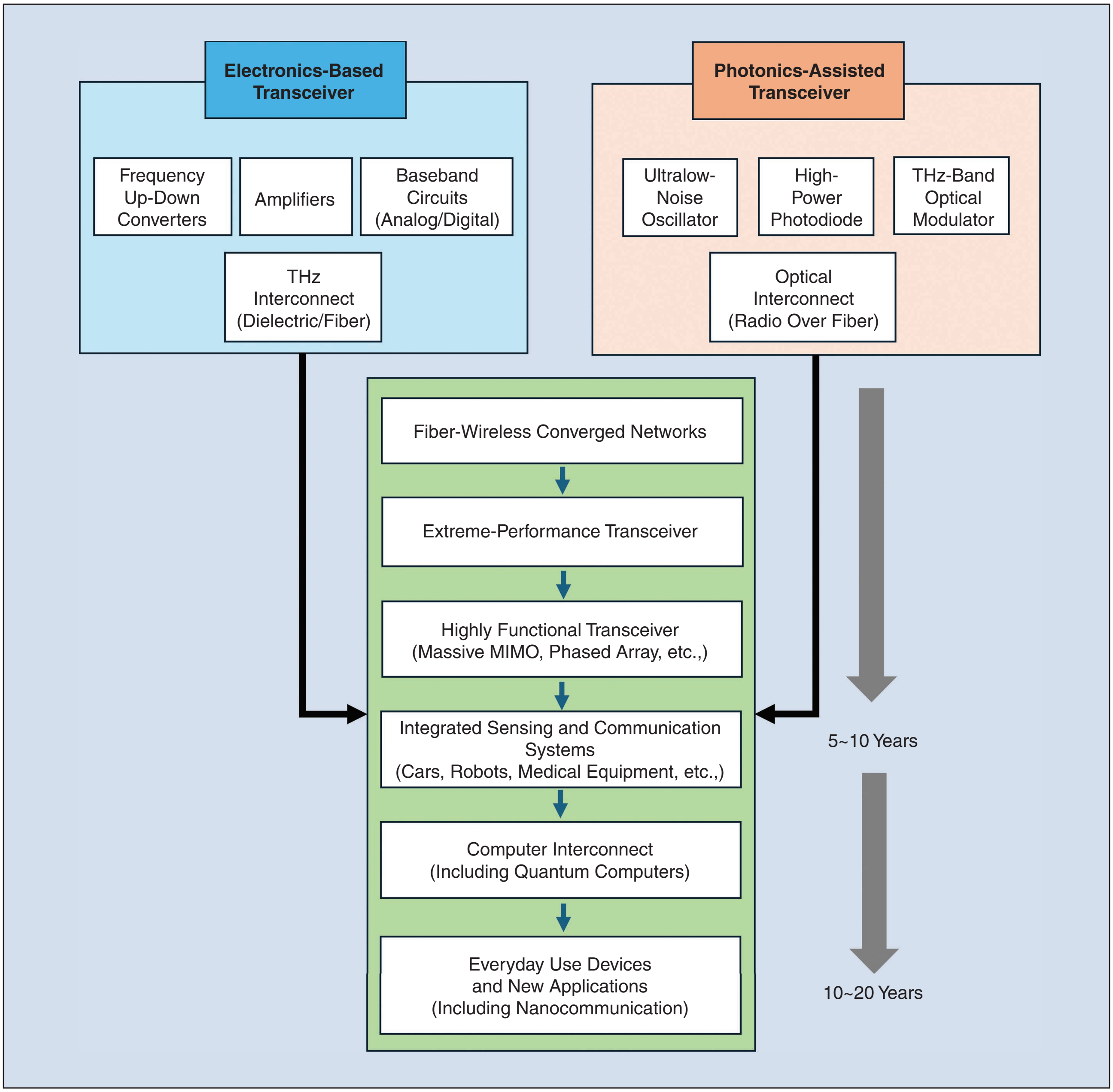

FIGURE 3 Key devices that constitute electronics- and photonics-based transceivers, and the evolution of application technologies resulting from their integration and convergence. MIMO: multiple-input multiple-output.

AS RESEARCH AND DEVELOPMENT IN THIS FIELD ADVANCE, THE COST AND SIZE OF TRANSCEIVERS WILL LIKELY DECREASE SIGNIFICANTLY, MAKING THz COMMUNICATION A COMMON FEATURE IN EVERYDAY LIFE.

a typical application of this technology. Over the next 10 to 20 years, it is expected that both wired and wireless, as well as optical and radio wave technologies, will merge in transmission systems for computers and information devices. As research and development in this field advance, the cost and size of transceivers will likely decrease significantly, making THz communication a common feature in everyday life. Last but not least, it is relevant to mention that new materials and physics will also enter the game. For example, plasma waves in III-V semiconductors, graphene, and other 2D materials also offer interesting opportunities for terahertz device technology. For example, plasma waves at THz frequencies can be excited directly with a dc current in a high electron-mobility transistor with asymmetric boundary conditions [9]. Similar devices can be used to modulate plasma waves in amplitude, phase, or frequency before being radiated by a plasmonic or subwavelength antenna. Moreover, the compact size of plasmonic devices allows their integration in very compact footprints, opening the door to equally compact antenna arrays. While these technologies are still at a fundamental stage, they will enter the game in the decades to come.

Analog and Digital Signal Processing Convergence

Today, we primarily use THz communications to transfer digital information between computers that follow a von Neumann architecture. Therefore, digital-to-analog and analog-to-digital interfaces are needed. In recent years, there have been two parallel trends relating to where that conversion should occur. On the one end, many efforts have been aimed at moving all of the signal processing to the digital domain. For example, in current sub-6-GHz radios, all of the signal processing is done digitally before the digital-to-analog converters (DACs) convert digital IQ streams into analog streams that feed an IQ mixer for an analog local oscillator (LO). In some instances, the LO or carrier signal itself is digitally generated. A reciprocal architecture is used at the receiver, where data are immediately digitized after an analog IQ mixer or even before, at radio frequency, right after the antenna, by an analog-to-digital converter (ADC).

While going fully digital allows for fully reconfigurable radios, there is one major bottleneck in this approach as we move to larger bandwidths, namely the sampling frequency of DACs and ADCs [10]. Today, data converters able to sample at frequencies above 100 Giga-samples-per-second are commercially available. However, their cost, size, and power requirements limit their application to lab equipment or bulky prototypes (i.e., far from handset devices). To overcome this challenge, parallelized architectures using multiple data converters can be utilized before an analog frequency or time multiplexing stage. In any case, the situation becomes even harder when aiming for multiple-input multiple-output (MIMO) systems.

On the other end, to overcome the speed limitations and power requirements of data converters, there has been a shift toward fully analog signal processing. In this case, instead of generating IQ streams to be converted, digital control lines are utilized to directly modulate an analog LO as close to the antenna as possible. For example, one- or two-bit phase modulators can be utilized to generate phase shift-keying modulations or even amplitude-phase shift-keying modulations when adding a 1-bit gain controller [11]. This is substantially simpler than utilizing two DACs (for I and Q streams) with 8 to 12 bits each. At the receiver, a similar structure is needed to demodulate the received signals analogically.

The approach described previously still presents many challenges. For example, while simple amplitude and/or phase modulations are easy to implement, modulations with higher spectral efficiency, such as orthogonal frequency-division multiplexing (OFDM), discrete Fourier transform-spread-OFDM, or orthogonal time-frequency space, cannot be easily implemented. In addition, common signal processing aids, such as channel estimation and equalization, are harder to implement in the analog domain. On the positive side, the fact that THz channels are generally much more directional and, thus, experience lower multipath, these aspects might be easier. There are many tradeoffs to study. Last but not least, programmability becomes much harder.

To overcome the challenges, a hybrid approach is needed. For example, new pre- and postequalization techniques that act on the few bits utilized at the transmitter and recovered at the receiver need to be developed, taking into account that now the channel abstraction has a much lower resolution than that obtained from a high-resolution data-converter. Then these techniques need to be extended to the MIMO case. Ultimately, in all cases, signal generation, modulation, amplification, radiation, and detection need to be jointly designed and analyzed. To support this integrated design, machine learning can offer adaptive and predictive solutions by dynamically adjusting key system parameters, such as modulation schemes, signal power, and equalization in real time based on the channel's current state. Reinforcement learning algorithms, for example, can help the system learn from changing conditions, enabling intelligent adjustments that improve efficiency and reduce errors. By leveraging historical data and environmental feedback, machine-learning models can predict future channel states and preemptively modify transmission strategies, ensuring optimized performance in fluctuating and complex environments, such as those in THz communication and MIMO systems.

Mobile ISAC

Doppler Effects in Mobile THz Systems

Terahertz bands not only offer the potential for ultrahigh data rates, but also excel in environmental sensing. The immense bandwidth available at THz frequencies enables high-precision radar systems, while the variation in reflection and transmission properties across different frequencies allows for detailed environmental characterization. This unique combination opens numerous opportunities to integrate communication with advanced sensing, imaging, and localization functionalities, which typically have restricted resolution at lower frequencies [12].

However, despite the many attractive properties of sub-THz and THz bands for both sensing and communications, these frequencies also present unique challenges. As extensively discussed in the literature, those arise directly from the increased carrier frequency and require innovative solutions for effective deployment. One of the challenges is the presence of more intense Doppler effects in such channels. The strong Doppler shifts alone are not as much of a problem because they can be jointly compensated with the carrier frequency offset.[1] A more severe issue is caused by intense Doppler spread, which is hard to compensate for and is responsible for decreasing the channel coherence time. However, the Doppler spread is a function of the mobility within the wireless link, which means that static links are not affected. On the other hand, mobile THz links will require an effective strategy to overcome the problems that result from such effects, doing so without spending excessive amounts of energy and processing time.

The intensity of the Doppler shift f_D is given by the expression

$$f_D = \frac{v}{c} f_C \quad (1)$$

where v is the relative speed between transmitter and receiver, c is the speed of light, and f_c is the carrier frequency. Thus, a receiver moving at 100 m/s and operating at 30 GHz experiences the same Doppler shift as a similar receiver moving at 10 m/s at 300 GHz. This means that the channel coherence times typical of medium- or high-mobility scenarios in the millimeter-wave (mmWave) range can now be experienced in the low- and medium-mobility regimes in the sub-THz and THz ranges. For example, at 300 GHz, a relative velocity of 10 m/s (typical of a motor vehicle in an urban region) produces a channel coherence time in tens of microseconds. This ordinary scenario would already impose a heavy channel estimation overhead using traditional channel estimation methods, requiring extremely frequent updating of the channel state information. This indicates that the usual channel estimation procedures are likely unfit for mobile links in the sub-THz and THz bands, which we call *strong Doppler channels*. Therefore, it is relevant to understand the effects of strong Doppler on both sensing and communications and how the interplay of both areas may lead to an elegant solution to the aforementioned issues.

Integrated Sensing and Communication

Wireless sub-THz and THz channels in many conventional applications are quasi-optical, which means they exhibit very similar characteristics to visible light. Such channels are typically LoS-dominated and sparse, containing only a few multipath components [13], [14]. These properties make it possible to directly relate the parameters of the multipath components, such as angle of arrival, angle of departure, time of flight, and Doppler shift, to the geometry of the channel itself, strengthening the link between channel estimation and sensing. Furthermore, the core components of the channel geometry, such as the angles of arrival and departure, change much more slowly than the instantaneous carrier phase shifts caused by the channel. Therefore, the channel geometry can be considered fixed for a significantly longer time than the instantaneous channel state. This property should be exploited for communications and sensing purposes. For example, a known channel geometry can assist in estimating and predicting the channel tensor and the localization/sensing target positions.

Conventional channel estimation relies on estimating the channel matrix/tensor, which contains the compounded effects of all of the multipath components. It also requires that the channel tensor values remain approximately constant throughout the estimation period, which should also be much shorter than the channel coherence time. If we take the previously considered example scenario, the channel would have to be estimated at approximately every couple of microseconds, and the transmitted symbols should be only a few nanoseconds long. This clearly is not a resource-efficient approach. As an alternative, parametric channel estimators decompose the channel into its separate multipath contributions and are not affected by such problems. Those methods are able to effectively estimate the channel as long as the multipath parameters remain mostly unchanged. Their main drawback is their associated computational complexity and, consequently, time. Therefore, the development of fast and efficient parametric channel estimators for strong

[1] Such compensation usually makes it impossible to separately estimate Doppler shifts and oscillator differences. Thus, it only fits for communications applications and not directly for sensing and localization.

Doppler channels is crucial for the eventual deployment of THz links in medium- and high-mobility scenarios. Also, other major challenges need to be addressed. For example, ultrawideband transmission makes not only the propagation channel but also the transceiver hardware and antenna array frequency selective. The current channel estimation and measurement approaches are not capable of handling such a situation.

Parametric channel estimation in strong Doppler scenarios is also more challenging than in approximately time-invariant channels. In time-invariant channels, it is possible to estimate the channel tensor using least-squares methods and pilot sequences and then use computationally efficient tensor decompositions to solve for the harmonic components, which correspond to the multipath parameters. In strong Doppler, however, the channel tensor cannot be directly estimated because the channel varies in time during the transmission of the pilot sequence. The aforementioned tensor methods cannot be directly applied, and one must solve the more challenging indirect multidimensional harmonic retrieval problem, in which the channel tensor cannot be directly observed and only its effects on the received signal are seen. Efficiently solving the indirect multidimensional harmonic retrieval problem (or finding clever ways to circumvent it) is necessary to enable mobile integrated sensing and communication in the THz range.

Sensing and localization are time-critical applications in which information can become outdated in tens of milliseconds. Thus, accurate channel estimates must be available in a couple of milliseconds. This means that most of the processing should be made at the base station (BS), which has superior processing power and possibly dedicated hardware. Consequently, it seems efficient for the BS and user equipment (UE) to use the same frequency resources and operate in time-division duplex or full-duplex, exploiting the channel reciprocity and saving computational effort. This also favors the sensing setups that have a BS as a receiver, such as bistatic uplink sensing, BS–BS sensing, and monostatic BS sensing. While the commercial applicability of BS–BS sensing is questionable,[2] its usefulness in terms of sensing is undeniable due to the larger transmitter power budget and the possibility of sharing clocks and oscillator signals. Uplink sensing, on the other hand, appears to make more economic sense, but has to deal with lower signal-to-noise ratio and clock and carrier frequency offsets. Monostatic BS sensing has limited localization capabilities and is only able to detect passive targets; its information may, nonetheless, be used through sensor fusion methods, enhancing the sensing accuracy of the whole system. Studying the integration of different types of sensing and their technical and economical viability is a relevant research topic, not only for mobile sub-THz and THz systems, but for ISAC in general.

An example of uplink sensing and parametric channel estimation is shown in Figure 4, using an OFDM waveform. However, as mentioned in previous sections, various practical challenges prevent its direct implementation in systems operating in the sub-THz band. We emphasize that the use of OFDM here is for technical convenience, and parametric channel estimation methods can be applied to a wide range of waveforms, including single-carrier schemes. Advances in hardware for signal processing in these frequency ranges will progressively enable more sophisticated communication and sensing setups. In this example, the UE is moving at 25 m/s and transmitting a pilot sequence at 300 GHz. The sequence consists of 24 OFDM symbols with 12 subcarriers spaced 240 kHz apart. The UE and BS are equipped with four and 32 antennas, respectively, arranged in a uniform linear array. For simplicity, clock and carrier offsets are assumed to be fully known. The estimated LoS path parameters are used to compute the UE's position and orientation, while the multipath parameters are used to estimate the reflector positions and the UE's velocity. The progression of the parametric channel estimation process is depicted in Figure 4(b) and (c). Figure 4(b) presents the negative log-likelihood objective function of the channel estimator as a function of the estimator iterations. Similarly, Figure 4(c) shows the progression of the absolute error of the parameters of each of the five ground truth paths. Estimation is performed using a variation of the space-alternating generalized expectation-maximization algorithm for OFDM [15]. This type of parametric channel estimation can be leveraged sequentially for localization, sensing, and mapping (LSM).

Localization, Sensing, and Mapping

Beyond estimating the multipath parameters in a single instant, a sequence of measurements in time can be used to extract additional information. Using sophisticated signal processing and inference methods, a system can be made to track sensing targets, map the environment and its materials, and estimate the position of active devices. These activities, however, incur a significant computational cost. This happens because solving the problem of simultaneous LSM (including active and passive target tracking) is extremely challenging, and most algorithms are either too simple and ineffective or quite complicated but computationally expensive. Therefore, to ensure the widespread deployment of mobile sub-THz and THz ISAC to its full capabilities, significant attention must be dedicated to developing and implementing sequential inference algorithms for LSM.

It is clear that communications in mobile sub-THz and THz systems are deeply tied to LSM. Information

[2]It is often inefficient in terms of coverage to deploy BS within the LoS of each other except possibly in some rural environments.

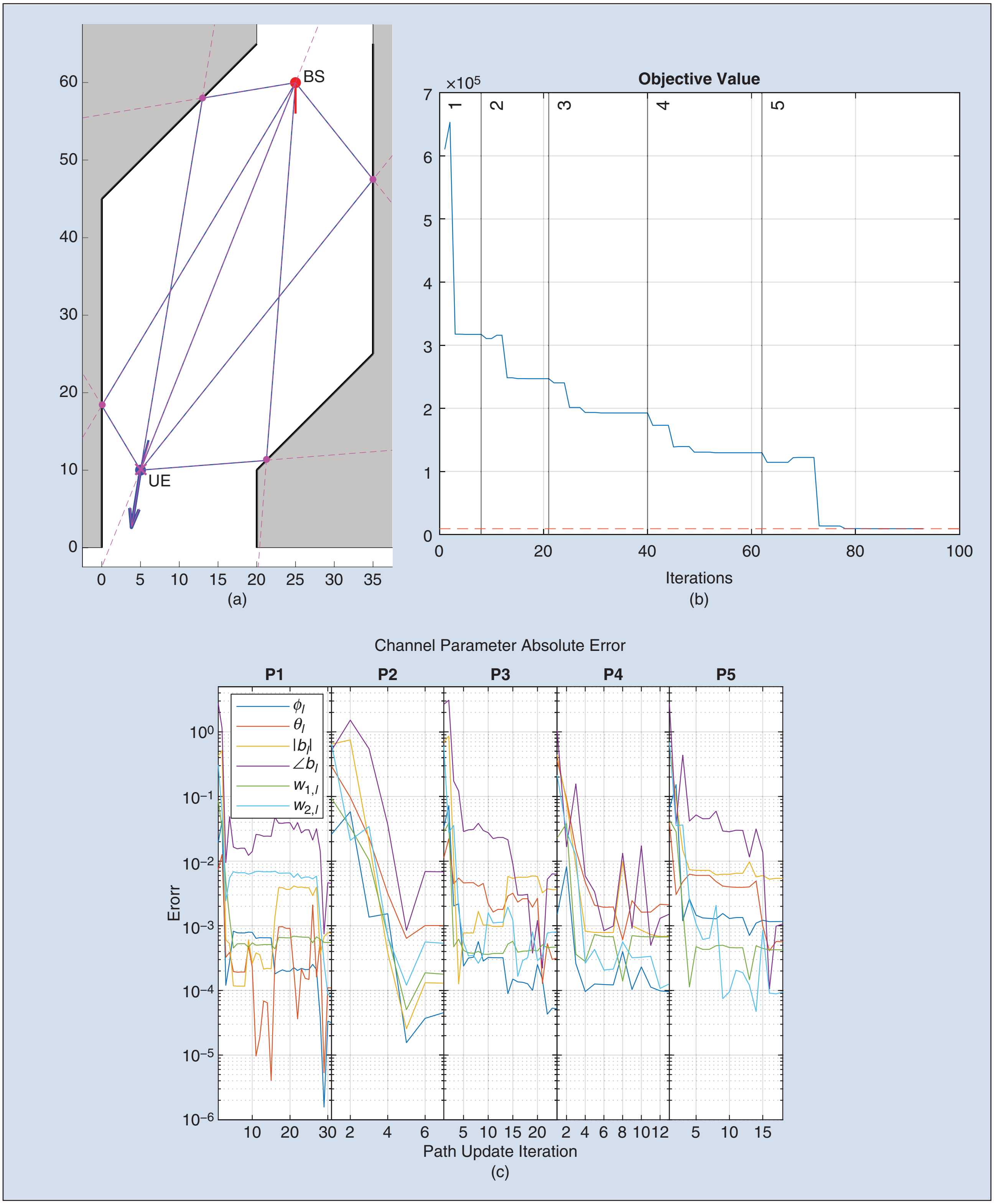

FIGURE 4 Example scenario of using a parametric channel estimator to perform localization and mapping/sensing. The localization and sensing information is shown in (a). The details of the channel estimation process are shown in (b) and (c), representing the progression of the objective function and path parameter estimate errors. (a) True (blue) and estimated (magenta) position, orientation, velocity, and multipath. Orientations are displayed by headless arrows while velocities are normal arrows. The expected positions of the reflectors are shown as magenta circles. (b) Objective function of the channel estimator. The vertical lines indicate that a new path was added. The dashed red line is the expected minimum objective. (c) Absolute error of the parameters of each path, ϕ and θ are the AoA and AoD, b is the complex path coefficient, and $\omega 1$ and $\omega 2$ are the ToF and Doppler parameters (including offsets).

Rather than relying on traditional static spectrum allocation, the dynamic nature of THz applications calls for more agile and flexible spectrum management techniques.

about the environment can be used both to improve connectivity, such as channel estimation and prediction, and for sensing purposes. There are two possible future approaches for the LSM in THz bands. One option is that the types of processing previously exclusive to channel-sounding campaigns, such as parametric channel estimation and mapping, may become routine to overcome the low channel coherence times that arise from high Doppler spreads. Although these methods are computationally more complex than the typical channel estimators for communications, they provide valuable information that can be leveraged for LSM. From this perspective, it can be understood that ISAC is a natural consequence of the challenges and opportunities that arise from mobility in the sub-THz and THz bands. The other option can be to utilize new artificial intelligence (AI) tools to facilitate the process. For example, generative AI models can be used to predict the environment and the channel from a few observations of the same. While other AI methods may also contribute to channel modeling and prediction, generative AI's ability to extrapolate from limited data and generate realistic estimates makes it particularly suitable for the challenges faced in the THz spectrum. The challenge in this case is posed by the amount of information and electricity needed to train such generative AI models. Therefore, the methods should make major progress in data and energy efficient model training and generalization.

Channel Characterization and Spectrum Sharing

The success of LSM in mobile THz systems relies heavily on a precise understanding of the channel environment.

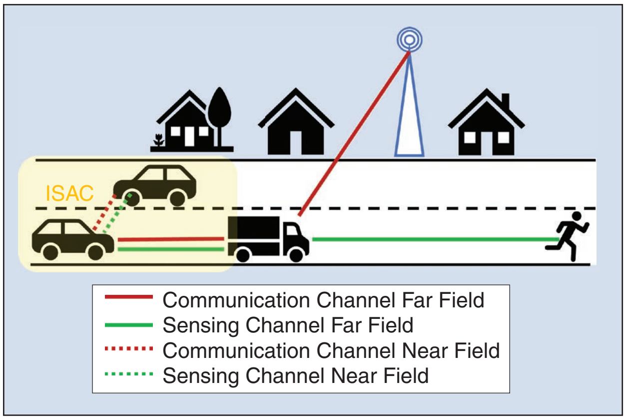

FIGURE 5 Exemplary scenarios for channel characterization taking into account near-field effects, ISAC, and mobility.

The dynamic nature of THz communication channels requires continuous refinement of both sensing and communication processes, making comprehensive channel characterization a critical component of effective LSM techniques. However, only a few initial measurements of time-variant channels beyond 275 GHz have been conducted so far (see, e.g., [16]). To make mobility in THz systems feasible, the characterization of the time-varying channel is essential. Time-variance can stem from two primary sources: the movement of the transmitter or receiver and the movement of scattering or blocking objects.

For the dimensioning of backhaul links, which may be one of the early applications of THz communications, the impact of rain causing significant additional path loss must be considered [17]. Since backhaul links need to be planned for high reliability, the increased path loss under rainy conditions is the critical factor when setting up the link budget.

For comprehensive measurements of such scenarios, mechanical steering of antennas must be replaced by electronic steering using massive MIMO arrays. Yet, the development of antennas at THz frequencies remains in its infancy, as discussed in the "Convergence in Terahertz Technologies" section. Moreover, ISAC concepts require channel characterization for both sensing and radar systems, which differs significantly from traditional communication channel characterization. Combined sensing and communication channels need further exploration, especially in environments with massive MIMO antennas and reconfigurable intelligent surfaces (RIS). At these frequencies, the larger apertures lead to near-field conditions, which complicates the derivation of THz channel models, particularly when factoring in ISAC requirements and mobility, as shown in Figure 5.

Furthermore, the spectrum above 275 GHz is of increasing interest not only for communication but also for passive services, like radio astronomy and Earth exploration satellite services. As ISAC seeks to merge communication with sensing, imaging, and localization, it introduces complex spectrum-sharing challenges. Addressing these requires a paradigm shift in spectrum management. Rather than relying on traditional static spectrum allocation, the dynamic nature of THz applications calls for more agile and flexible spectrum management techniques. Although initial ideas for such approaches have been proposed [18], significant research is still required to develop practical, implementable solutions. However, the fact that not many THz installations are currently available in this frequency range presents an opportunity to implement methods in a "sandbox" approach.

Dynamic Beam Shaping and Wavefront Engineering

To realize the aforementioned communication and sensing capabilities, THz systems must be able to precisely control EM radiation at the transmitter, through the channel, and at the receiver. In this section, we highlight that users in THz systems might transition between the near- and far-field regions of each other, review the concept of wavefront engineering and its role in beam shaping, and discuss effective ways to realize new beams.

Near- and Far-Field Regions

The fundamental antenna theory remains valid at THz frequencies. Accordingly, if we want to radiate a THz signal omnidirectionally, we need a half-wavelength dipole. For example, a 0.5-mm-long dipole resonates at approximately 300 GHz. The problem is that when utilizing the same antenna in reception, the very small physical area of the dipole results in very low received powers. To capture higher amounts of power, we can increase the antenna size. However, when increasing the size of an antenna, it intrinsically becomes directional. This is not a problem when designing a static link with LoS conditions, but makes mobile networking significantly harder, as we need to constantly collect information about our environment to properly know "where to point." As we just discussed in the previous section, this is why joint communications and sensing have become a necessity and not just a feature.

There is one more aspect that changes when utilizing larger antennas. Traditionally, the users in a wireless system are in the so-called *far field* from each other. There are many ways to define where the far field starts, but a common approach is to utilize the Fraunhofer distance. The Fraunhofer distance of a radiating system is defined by $2D^2/\lambda$, where D is the antenna's largest dimension and λ is the signal wavelength. For example, a 10-cm antenna or antenna array at 120 GHz has a near field of 8 m. At 300 GHz, the same antenna has a near field of 20 m. Similarly, a 1-m antenna or antenna array (e.g., in a BS) or a large reflecting surface (e.g., in windows and walls) at 120 GHz has a near field of 800 m (2 km at 300 GHz). Clearly, many users in THz applications will be in the near field or moving across the near and the far fields. More than being a challenge, the operation in the near field opens the door to new types of beams.

Beams and Wavefronts

In traditional microwave communication systems, omnidirectional emitters radiating near-spherical waves are considered. A receiver in the far field does not perceive the curvature of the wave and, thus, plane waves are commonly assumed. This assumption is at the basis of most beamforming techniques for antenna arrays with omnidirectional elements. When it comes to fixed directional antennas, Gaussian beams are commonly utilized.

At THz frequencies, researchers have investigated many options, including narrow pencil-like beams, multibeam signals, and diffuse random wavefronts, for various applications where the target is located in the far field of the emitting aperture. In the near-field case, even more possibilities can be explored beyond spherical and planar waves or Gaussian beams. These include energy-efficient focused beams [19], self-healing Bessel beams that can recover from blockage [20], and self-accelerating beams that follow curved trajectories [21]. The ability to generate and, in some cases, switch between various beams will be a foundational requirement for future wireless systems.

In addition to beams, many works at THz frequencies utilize the concept of wavefronts. A wavefront represents a surface of constant phase within the propagating wave. The beam, on the other hand, defines the overall direction of energy flow and is composed of a collection of such wavefronts. Crucially, the wavefront is always oriented perpendicular to the direction of the beam propagation. This orthogonal relationship is fundamental in understanding beam behavior, as the shape and curvature of the wavefront directly dictate phenomena, such as diffraction, focusing, and interference. In idealized scenarios like a perfectly collimated beam, the wavefront is planar, while diverging or converging beams exhibit curved wavefronts.

Unlike signals at lower frequencies, wavefronts at THz frequencies can vary rapidly as a function of position on a length scale smaller than the typical dimensions of UE or obstructions (e.g., centimeter scale). This rapid variation in the amplitude and/or phase of a wave can be exploited for imaging and sensing, as well as for communications, offering opportunities, such as high-resolution target location or data links with enhanced security, as we discussed in the "Mobile ISAC" section.

Manipulation of Wavefronts

To enable these capabilities, the physical layer will need to manipulate the amplitude and/or phase of a wavefront at multiple separate points in space; a single-point transmitter or modulator will not suffice. This requirement is already well known for MIMO architectures and phased antenna arrays, where signal generation and wavefront manipulation are traditionally performed by the same components. At higher frequencies, it may be advantageous to separate these two tasks so that signal generation and wave manipulation are performed by distinct components. Allowing for the possibility that engineered amplitude and phase modulation (requiring multiple elements) can be separated from signal generation (which can thus comprise only a single emitting element) can significantly relax the demands on the radiation source. This separation can offer improved energy efficiency without sacrificing other performance metrics, such as speed, reconfigurability, and operating bandwidth.

This line of thinking motivates the idea of a planar array of elements that can create a (possibly complex) target wavefront by scattering an incident wave that arrives with a simpler wavefront. One can envision an architecture in which a single transmitter generates a high-power wave at a chosen frequency in the mmWave or sub-THz range with a relatively simple (e.g., spherical) wavefront. This wavefront then interacts with the planar array, producing a scattered wavefront that may be more complex and useful. Such planar arrays go by many names, sometimes distinguished by whether the elements are spaced by more or less than $\lambda/2$, and whether the array operates in transmission or reflection.

In any case, the goal is to produce a complex (and possibly dynamically reconfigurable) wavefront with the desired attributes, such as directionality or focusing. For communication links, data modulation could be applied by the signal source, in which case the wavefront generation must provide uniform operation across the bandwidth of the modulated signal. In this scenario, the device could be static or switch at relatively slow speeds (e.g., kilohertz) to accommodate mobility. Alternatively, data modulation could be imposed by the wavefront-generating array itself, for instance, by dynamically reconfiguring this multielement device at the symbol rate (e.g., gigahertz). Clearly, the demands on such devices can vary widely depending on the intended system implementation.

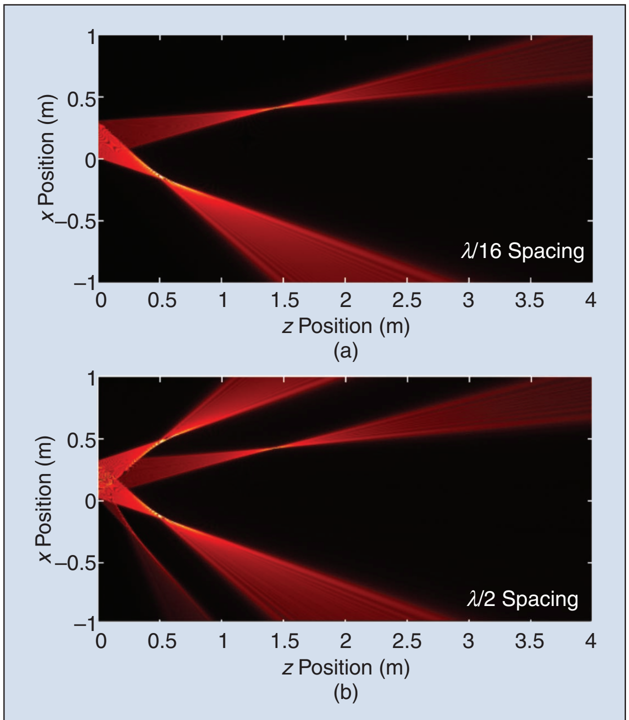

FIGURE 6 Multifocal beam generation using a 30-cm metasurface located in the $z = 0$ plane. (a) Meta-elements spaced at $\lambda/16$ produce two beams with distinct focal points. (b) Meta-elements spaced at $\lambda/2$ generate the intended near-field wavefront (two focal points), along with additional undesired artifact beams, due to undersampling of the amplitude and phase profile in the aperture plane.

RISs for Wavefront Engineering

Several novel aspects of this approach have emerged in recent years. One example involves the distance between the source and the modulating array. In most conventional reflect-array configurations, these are in relatively close proximity, such that the two distinct elements can be envisioned as components of a single module (i.e., the two elements together are often described as a *single antenna*). A somewhat newer idea is to envision the two as being widely separated, for example, on opposite sides of a room. This concept leverages the idea that highly directional beams can be generated by a single emitting element (especially at high frequencies), so that a remotely located array can still intercept a significant fraction of the emitted power. These RIS can provide significantly enhanced channel diversity at frequencies above 100 GHz, where many typical environments offer only relatively sparse scattering [22].

Interestingly, although RIS devices are often described using the term *metasurface*, this term, strictly speaking, applies only to arrays with element spacing less than $\lambda/2$. The terminology originates from the idea of a bulk (3D) collection of subwavelength elements whose dimensions are small enough so that the entire structure can be described using a homogenized model with a well-defined permittivity and permeability. In extrapolating from this 3D picture to the 2D analog, the terminology was preserved (i.e., "metamaterial" became "metasurface"), although the homogenized quantities $[\varepsilon(\omega)$ and $\mu(\omega)]$ are generally no longer used. As a result, there is some confusion over what constitutes a *metasurface* and little uniformity in the usage of the term.

Regardless of terminology, it is clear that in many cases there is little advantage in building arrays with element spacing less than $\lambda/2$, as this is all that is required for Nyquist sampling. There are, however, a few exceptions to this statement. For one, some metamaterials (and metasurfaces) do not rely on a resonant response of the subwavelength elements to define their macroscopic properties. For example, many dielectric metasurfaces employ a similar homogenization formalism, as mentioned above. This can be advantageous in the case of broadband excitation, where a strongly frequency-dependent response could be undesirable. In addition, some near-field wave fronts may require elements with smaller spacing to accurately sample an amplitude and phase profile that vary rapidly in the aperture plane. An example is illustrated in Figure 6.

In these situations, metasurfaces are a critical component. Such devices, which can operate either in transmission or reflection, are otherwise similar in concept to reflect arrays: They are arrays of elements which, upon illumination by an external source, produce a scattered wave with a desired amplitude and phase response. This response can be tuned for each element in the array to produce a tailored outgoing wavefront, and in some cases can be dynamically reconfigured for wavefront switching. This versatility offers some solutions to the challenges faced by the RIS architecture, and may therefore enable more ready integration of these arrays in future communication and sensing systems operating above 100 GHz.

Prospective Applications

With the technological capabilities, mobility implications, and near-field effects all in mind, we can now discuss the use cases of mobile THz systems. The potential applications can be explored from multiple perspectives. These viewpoints reflect varying expectations for how THz frequencies will be integrated into future communication systems, driven by both technological advancements and practical constraints. In this section, we discuss three key perspectives—the "classical" view, the "pragmatic" technology-driven view, and the "use case-oriented" approach—each offering insights into how THz communication could unfold in the coming years.

For the "classical" point of view there is the ever-increasing data rate, known as *Edholm's Law* [23], which predicts that data rates in wireless systems are doubling roughly every 18 months. Applying this law, one can predict a data rate of 1 Tbps before 2035. Assuming a practically and area-wide achievable spectral efficiency of 10–20 bit/s/Hz, one can easily see the requirement for bandwidths of 50–100 GHz, which are available only beyond 275 GHz (note that with current regulations, in the 100—275 GHz, not more than 32 GHz of contiguous spectrum is available). This view assumes that THz frequencies are used the same way as frequencies in today's multipurpose Wi-Fi and cellular systems. However, the high path loss yields either short coverage distances or requires antennas with ultrahigh gain in the order of 40 to 50 dBi, which are hard to obtain in compact user devices as we know them today. For shorter-range links, for example, in indoor Wi-Fi–type scenarios, the main problem arises from the blockage of walls and other obstacles. In the "cellular" context, THz links will most likely be used only as complementary links to the lower frequency cellular links, as described, for example, in [24] as the local area collaboration use case for vehicular applications. These use cases opportunistically apply THz frequencies, as shown in Figure 7. Still, looking at the slow uptake of many standardized features in 5G due to the lack of business opportunities for cellular operators, it is obvious that to make THz frequencies attractive for cellular operators, they must have the clear potential to create a realistic business case for them.

The "pragmatic" point of view focuses on applications, where the abovementioned restrictions coming from the propagation environment are relaxed and/or can be easily mitigated and where technology is mature enough. This technology-based approach was taken in the development of the THz PHY in IEEE 802.15.3-2023 [25], which provides solutions for fixed-point–point links, such as wireless X-haul links, wireless links in data centers, intradevice communication, or kiosk downloading. For these applications, first hardware demonstrations in real environments have been performed. For example, in [17] a wireless backhaul link at 300 GHz with real transmission has been successfully demonstrated and a further evolution of this system targeting a more compact realization has the potential to be commercially competitive with the intensive and expensive deployments of fiber links. Hence, this makes these applications the ones we will see most likely in about 10–15 years.

The "use case oriented" point of view focuses on scenarios where THz frequencies are the key enabler, as taken by ETSI Industry Specification Groups THz in its Group Report 001 [24]. In this report, a total of 19 use cases mapped to nine application areas have been identified. Among these use cases and application areas, the feasible applications mentioned in the "classical" and "pragmatic" points of view above are included as well. For each use case, the report provides insight into deployment scenarios, potential requirements, and the operational propagation environments. Furthermore, the report identifies key enabling technologies and maps the identified use cases and deployment scenarios to relevant channel measurement scenarios, aiming to derive the necessary channel models while simultaneously addressing standardization requirements.

In the following, two exemplary applications derived from the "use case-oriented" point of view with a high potential to be operated at THz frequencies in 2035 to 2040 are briefly described. Note that these applications do not necessarily require a driver from the cellular

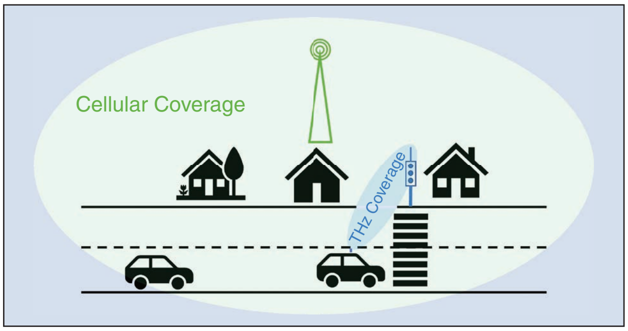

FIGURE 7 Opportunistic use of THz links for off-loading in a vehicular environment.

NANOCOMMUNICATION IS, THEREFORE, EXPECTED TO PLAY A PIVOTAL ROLE IN INTERFACING THE BIOLOGICAL, PHYSICAL, AND DIGITAL DOMAINS, BRIDGING THE GAP BETWEEN LIVING SYSTEMS AND ADVANCED TECHNOLOGICAL DEVICES.

industry, as they are of interest to other industries as well. The two exemplary applications are:

- *eXtended reality (XR):* XR is a set of technologies consisting of augmented reality, virtual reality, and mixed reality, which require high data rates, ultralow latency, and high reliability [24]. From a consumer point of view, XR is emerging in various applications, for example, at touristic places [26]. This enables users to experience cultural heritage explorations, such as at the Colosseum in Rome, in the way it was seen hundreds of years ago while walking through the site using geo-referenced virtual reality glasses. While this might work for a single user in a geographically small environment, serving hundreds of users simultaneously brings up the problem of scalability. Here, THz frequencies will be a key enabler to solve this issue. A precondition to making this happen is that the required hardware must be affordable for the operator of the touristic place.
- *Enhanced communication in industrial environments:* In industrial environments, machines, production lines, robots, and control centers are typically connected via cables. This setup is quite inflexible and brings challenges when movable parts are involved. Additionally, the high amount of data that needs to be exchanged, along with the ultrahigh requirements on latency and reliability, pushes current wireless systems to their limits. Hence, wired connections can be replaced with wireless communications at THz frequencies [24]. However, the cost of the THz hardware and its deployment must be attractive for the owner of the industrial plant from a business point of view.

Terahertz Systems to the Extremes

The potential of THz mobile communication extends far beyond traditional macroscale applications, with the THz frequency band pushing the boundaries of connectivity to the extremes, enabling diverse applications from the nanoscale to outer space, as shown in Figure 1. The fundamental enabler of both applications is, in fact, the same: the very small wavelength of terahertz radiation, which enables very small omnidirectional antennas and compact, very high gain directional antennas. We elaborate of these two extreme applications next.

Nanoscale Communication

Nanomaterials and nanostructures exhibit unique electrical and thermal properties that are not present at larger scales. By harnessing these novel properties, it becomes possible to create ultracompact devices, including signal nanogenerators, nanoantennas, nanopatterned surfaces, and nanophotodetectors, to name a few, at THz and optical frequencies [27]. These devices form the foundation for a network infrastructure that enables coordinated actions, distributed sensing, and collaborative functionalities, ultimately realizing the concept of the "Internet of Nanothings." Nanocommunication is, therefore, expected to play a pivotal role in interfacing the biological, physical, and digital domains, bridging the gap between living systems and advanced technological devices.

At the heart of nanocommunication is the nanomachine, which serves as its foundational component, typically combining nanosensors and nanoactuators. These elements can function as mobile health monitoring stations, capable of continuously tracking and responding to physiological changes within the body. For instance, nanosensors could monitor glucose levels in diabetics, identify circulating biomarkers related to cancer, or detect subtle changes in blood composition that indicate the onset of cardiovascular diseases. Meanwhile, nanoactuators could be designed to trigger the repair of damaged tissues or modulate immune responses, offering new approaches to treating autoimmune diseases or enhancing wound healing. Currently, many biomedical applications, such as optogenetics and optogenomics, rely on light to precisely target neurons and control gene expression to modulate cellular activity. However, this often requires the genetic modification of tissues to introduce light-sensitive proteins. Our vision extends beyond this, as we are investigating the use of THz signals and their ability to trigger resonances in proteins for nanobio-actuation. This offers a noninvasive alternative by potentially bypassing the need for genetic modification while achieving control over cellular processes.

While researchers over the past decade have made significant strides in modeling propagation and characterizing the intrabody THz channel [28], more work is needed to effectively interface the intrabody and on-body networks. System-level designs are required where external gateways are synchronized with nanosensors to ensure seamless transmission of information, especially given the challenges posed by the different timescales at which interactions in the body occur. In addition, as nanosensors move within the dynamic environment of the human body—carried by the flow of bodily fluids—their relative velocity with respect to cellular motion can induce a Doppler shift. This shift alters the frequency of the transmitted THz signal, potentially leading to signal degradation if not properly addressed. Furthermore, the precise location of each nanosensor is crucial for ensuring accurate data transmission and reception. Given the small size and often large number of nanosensors involved, pinpointing their exact positions relative to an external gateway is essential for effective communication. Variations in location can lead to differences in signal strength, delays, and potential interference, all of which must be mitigated to maintain reliable performance.

Beyond the medical realm, there is a significant range of nonbiological applications for nanocommunication that will help shape the future of THz communication. One promising field is agriculture, where nanosensors can be used to monitor and detect the presence of harmful chemicals or pathogens in the environment with high precision. This capability would provide early warning systems for contamination or biohazard exposure, enabling timely interventions to prevent widespread issues. In parallel, nanoactuators could be utilized to release nutrients or pesticides at precisely targeted locations and times. This targeted approach is expected not only to optimize crop health and yield but also to minimize environmental impact by reducing the overuse of chemicals. The role of THz communication extends to enhancing real-time data transmission and processing, which is crucial for the effective deployment of nanoscale devices. By leveraging the high data transfer rates and low latency of THz communication, nanonetworks can achieve more efficient monitoring and control, leading to smarter and more responsive systems across various domains.

Next-Generation Satellite and Space Networks

On the other extreme, just as nanocommunication pushes the limits of nanoscale interactions, THz communication for space presents a transformative leap for satellite and space networks. Satellite communication systems have traditionally relied on very microwave frequencies (e.g., S-band). However, as the demand for large-scale constellations in low Earth orbit expands—driven by applications, such as global Internet coverage—the emphasis has shifted toward mmWave and optical technologies. Nevertheless, THz technology is presented as a solution to meet demands for spectrum and desire for high data rate space communication, which also meets the needs of the scientific sensing community [29].

Terahertz mobile communication offers distinct advantages both for access links (up- and down-links) and intersatellite links. As discussed in the "Convergence in Terahertz Technologies" section, today, a THz radio can have the same transmit power as a Wi-Fi or 5G mmWave radio and, for the same footprint, it offers much higher antenna gains. As a result, it is easier to close an outdoor direct phone-to-satellite link with a THz radio than with a microwave radio. Of course, because of molecular absorption, that link cannot be at any frequency in the THz band but is mainly limited to sub-THz frequencies (between 100 GHz and 300 GHz). At true THz frequencies, the presence of many molecular absorption lines results in very high propagation losses through the atmosphere. Interestingly, when compared to optical signals, the much larger wavelength of THz signals (submillimetric versus submicrometric) results in much lower turbulence and scintillation losses.

Similarly, THz frequencies are advantageous also in intersatellite links, where a near-perfect vacuum eliminates molecular absorption, allowing both sub-THz and true THz signals to propagate freely. Even more interestingly, molecular absorption works to true THz signals' advantage since these cannot be jammed or eavesdropped by ground-based operators, making them a secure option for cross-link communication.

In addition, THz beams strike a balance between beamwidth and precision. They are narrower than microwaves, which reduces signal spread, but wider than laser beams, which demand highly precise pointing accuracy. This flexibility makes THz communication easier to deploy between moving satellites, where maintaining perfect alignment is challenging. Further, as the New Space Era drives the shift toward the deployment of small satellites, such as CubeSats, THz communication will play a critical role in meeting the size and power constraints of these platforms. In fact, the very small footprint of THz arrays (see the "Convergence in Terahertz Technologies" section) can contribute to footprint and weight reduction in CubeSats.

As we look toward the future of satellite technology, it becomes evident that progress in complementary areas will play a crucial role in enhancing overall communication capabilities. The innovations discussed in this work, from ISAC technology, which can help make efficient use of limited resources on satellites, to wavefront shaping, which enables satellites to maintain reliable communication links even as they move, are instrumental in shaping the future of resilient communication systems in the rapidly evolving space frontier.

Conclusion

In this article, we explored key research areas critical to advancing THz mobile communication. We began by examining the development of THz devices, highlighting how the integration of photonics and electronic technologies, along with analog and digital processing techniques, has driven the creation of high-performance transceivers and expanded their applications, from fixed wireless networks to advanced sensing and communication systems. Next, we discussed the inherent link between channel estimation and environmental sensing, emphasizing the potential of ISAC and LSM techniques in future networks. Channel characterization, particularly in mobile and dynamic environments, remains a critical area of research. Likewise, agile and flexible spectrum management will become increasingly important as THz frequencies are utilized for both communication and sensing, requiring innovative approaches to spectrum sharing and regulation. We also emphasized the importance of advanced wavefront engineering, which enables the manipulation of the amplitude and phase of THz waves for high-resolution imaging, secure communications, and enhanced beamforming. Achieving such precise control requires technologies beyond traditional single-element transmitters. Emerging solutions, such as phased arrays, metasurfaces, and RIS, are proving essential for wavefront manipulation, offering the flexibility to dynamically generate complex waveforms. As these foundations for THz mobile communication mature, the path forward reveals multiple prospective applications, shaped by technological advancements and practical constraints. Finally, we explored the broad potential of THz systems, from nanoscale applications to satellite and space networks, ensuring a holistic approach to THz mobile communication technologies.

While the first release of 6G may not see all of these challenges fully resolved, we believe this is not necessarily a setback. Building a functional mobile THz network requires time, and prioritizing thorough research and development over hasty solutions ensures a more robust and successful implementation in the long run.

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