Wavefront Hopping: An Enabler for Reliable and Secure Near Field Terahertz Communications in 6G and Beyond

Vitaly Petrov, Hichem Guerboukha, Daniel M. Mittleman, and Arjun Singh

Abstract

One of the principal differences between 5G-grade mobile millimeter wave (mmWave) and 6G (and beyond) terahertz (THz) band communications is the fact that the latter will often operate in the near field. This is because next-generation THz wireless solutions will have to keep the current physical size of the antenna systems or even increase them at the infrastructure side to combat spreading losses and maintain the desired performance and coverage for lower available transmit power and wider bands. A combination of a large antenna aperture and higher frequency increases the near-field zone around the transmitter. In the THz near field, the dexterity of wave propagation, characterized by the signal wavefront — the time-variant set of all points having the same phase — becomes important. The unique features and properties of these wavefronts provide an additional degree of freedom in system design. In this article, we present a novel concept of wavefront hopping to enable efficient, reliable, and secure THz band communications in the near field. Inspired by an existing "frequency hopping" concept, we show how a dynamic intelligent update of the utilized THz wavefront can work. We further illustrate how the use of this concept improves the characteristics of the THz link in various practical setups, and addresses some of the principal challenges of THz communications, thus making near-field THz communications more technologically and commercially attractive for 6G and beyond wireless networks.

Introduction

Despite relatively slow commercial adoption of millimeter wave (mmWave) radio systems, such as fifth-generation (5G) New Radio Frequency Range 2 (NR FR2) and 60 GHz IEEE 802.11ad/ay WiFi, mmWave communications are soon to become a part of the modern networking landscape [1]. MmWave radio presents one of the major novelties of existing 5G and prospective 5G-Advanced wireless systems boosting the peak data rates up to hundreds of gigabits per second. With the tentative target goal of one terabit per second peak data rate for sixth-generation (6G) and beyond wireless systems after 2030, the research community has started exploring even wider bands in sub-terahertz (sub-THz, 100 GHz–300 GHz) and THz (300 GHz–3 THz) frequencies [2].

The common understanding in the community is now converging toward the fact that, due to the spatial behavior of THz radiation, the requirement for high-gain directional antennas suggests the use of electrically large radiating structures, much larger than the wavelength [3]. Recalling that the far field of an antenna starts at distances greater than $2D^2/\lambda$, where D is the antenna's largest dimension [4], many mobile THz wireless systems will operate in the near field. For instance, a 10 cm antenna at 300 GHz has a far-field distance of 20 m, larger than many indoor environments in which a THz WLAN could be employed. Operation in the THz near field raises novel challenges [5], demanding novel near-field-specific techniques to complement or even replace beamforming, as the plane wave assumption is no longer valid.

However, it is wrong to consider operating in the THz near field as solely a research challenge to overcome. In contrast, fully embracing the near-field opens the door to impressive innovations that address some of the inherent problems of THz communications in a much "cleaner" way, directly at the physical and the medium access control (MAC) layers. One of these opportunities is the freedom of implementing the most appropriate wavefront — the spatial intensity and phase profiles of the signals being transmitted — dependent upon the link requirements. In the THz near field, the choice of the wavefront can significantly impact the key performance indicators (KPI) even if other parameters are the same [6].

Among the latest research undertakings on near-field THz systems, we already observe a clear pattern: *no single wavefront can be demarcated as providing optimal performance across the several practical link configurations that are likely in the THz landscape.* This is analogous to the phenomenon of waveform modulations: there is no single modulation that is exclusively the best; modern devices routinely switch between different modulations as the link parameters change.

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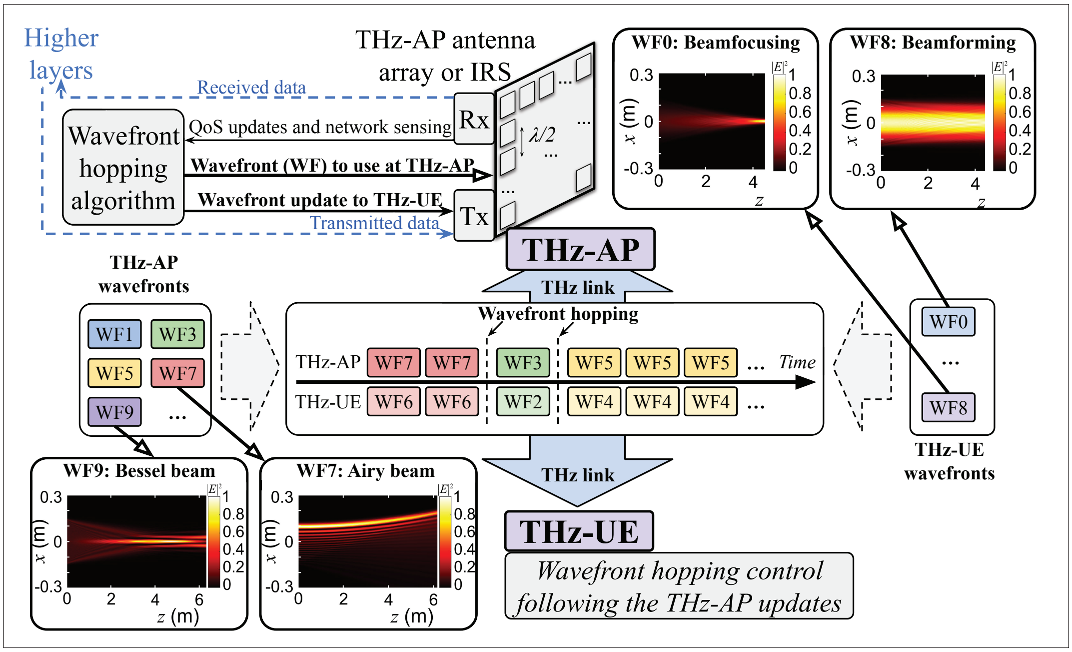

FIGURE 1. The concept of "wavefront hopping" for 6G and 6G+ wireless systems. THz access point (THz-AP) and the THz user equipment (THz-UE) synchronously adjust the used wavefronts (WFs) following an intelligent control procedure run at the THz-AP. The wavefront hopping algorithm run at the THz-AP: (i) decides on the new WF configuration to use; and (ii) prepares a control message to the THz-UE to coordinate the update of the UE WF as well.

Therefore, *in this article*, we make an important step from existing studies (including our work [6]) and argue for a similar philosophy with regard to the choice of the wavefront: instead of exclusively selecting one "best" wavefront for all setups, we need to design transceivers, necessary algorithms, and protocols capable of *dynamically switching among several pre-configured wavefronts*. We refer to this concept as "*wavefront hopping*" and advocate for it as an essential step toward successful implementation and massive adoption of mobile near-field THz communications for 6G and beyond.

Below, we first explain the concept of wavefront hopping. We then discuss how it can be used in THz networks for multiple purposes, including blockage mitigation, interference management, and physical layer security. We finally outline the key research challenges toward the successful implementation and adoption of THz wavefront hopping systems.

Wavefront Hopping

Recalling the Concept of a Wavefront

A *wavefront* is the imaginary line that connects all points of a wave with the same phase. It governs the beam shape and profile as it propagates. The wavefront of the transmitted signal can be adjusted by either the use of phase shifters at the antenna array or intelligent reflecting (or transmitting) surfaces (IRSs). The studies on modern 3G, 4G, and 5G wireless systems rarely deal with the wavefront; most of them assume far-field propagation and thus rely on the planar wave model. The signal wavefront becomes notably more important in near-field communications, including the emerging near-field mobile THz systems for 6G and beyond [7], as it affects the system characteristics and performance.

Rich Variety of Wavefronts for 6G+ THz Communications

Various wavefronts have been recently explored for THz and optical wireless systems with several examples illustrated in Fig. 1. Specifically, Fig. 1 presents four examples of the different wavefronts propagating from the transmitter to the receiver along the horizontal OZ axis. First, canonical *beamforming* is an applicable solution for systems operating in the THz far field and to facilitate the near-field to far-field users' mobility. Then, *beamfocusing* — focusing all the energy at a given fixed distance (instead of infinity, as canonical far-field beamforming does) — has been identified as a promising solution for stationary near-field THz links with little mobility.

In parallel, *Bessel beams* — focusing the energy not on a single point, but on a straight segment — have been found useful for mobile links in the near-field. Compared to beamfocusing, Bessel beams offer a greater depth of focus than conventional beamforming, providing a greater SNR, and better resilience to imperfect channel state information (CSI) in mobile setups compared to beamfocusing. They also feature self-healing capabilities, allowing to overcome partial blockage. The blockage can be further addressed with beams that can follow a curved trajectory, thus circumventing the obstacle. Airy-like beams [8] show great promise here. This list is non-exhaustive and there are other THz wavefronts available [6].

While the research on the suitability of different wavefronts for THz applications is still in the early stages, we argue that the most probable outcome is that *there is no perfect THz wavefront for all possible applications*. Some of the discussed wavefronts are inherently better for specific setups (e.g., beamfocusing for a momentarily static user in line-of-sight), while others outperform those immediately once the environment changes in the next moment. Therefore, we suggest shifting the commu-

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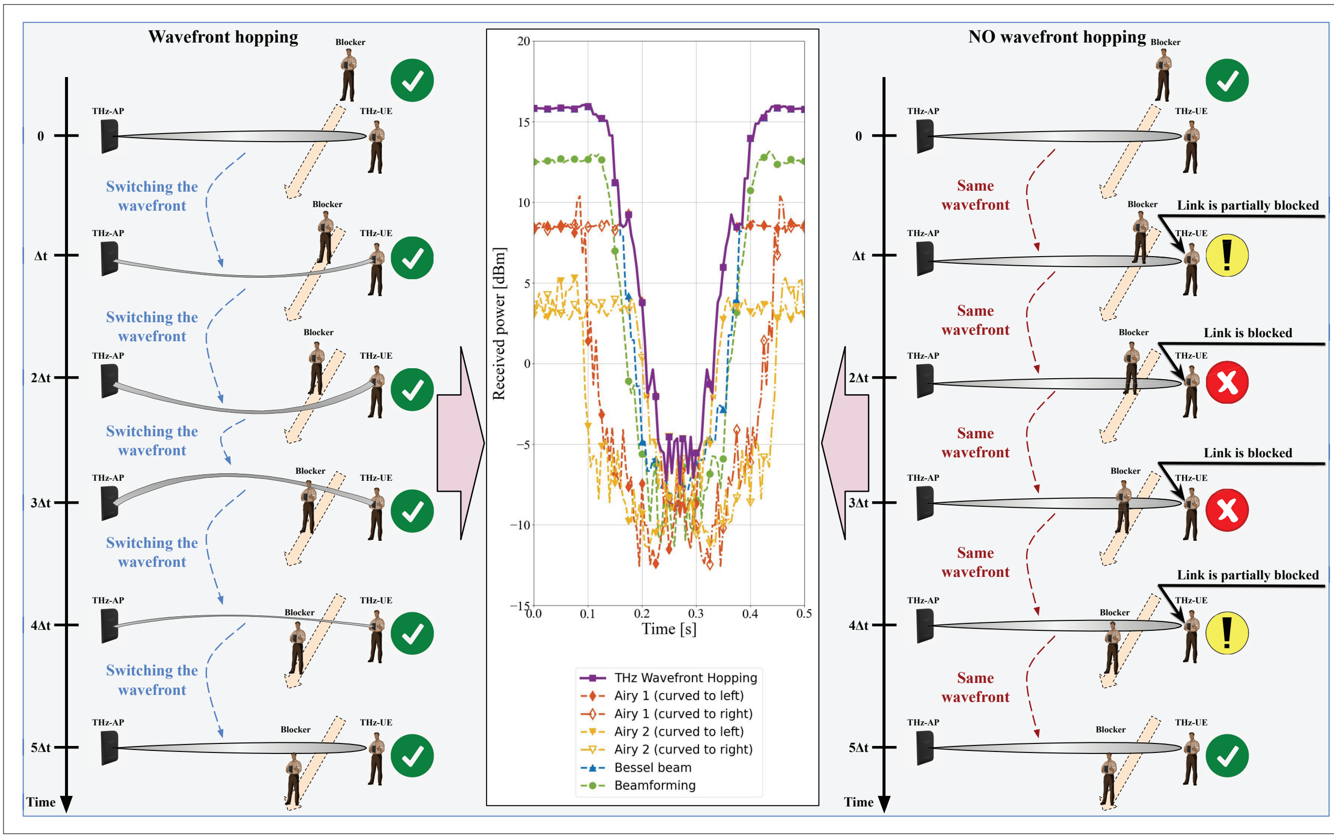

FIGURE 2. THz wavefront hopping to mitigate dynamic blockage. A high-level time diagram of wavefront hopping-capable THz system (left), non wavefront hopping-capable THz system (right), and first-order simulation results in the middle.

nity's focus from "engineering the most suitable THz wavefront" to a combination of: "identifying the minimal valuable set of practical wavefronts," and "developing an intelligent solution to dynamically hop amongst these wavefronts when needed." This research vision leads to the concept of *wavefront hopping* discussed below — the capability of a THz radio module to dynamically and quickly switch the current wavefront and/or its parameters to match the changing network conditions.

Wavefront Hopping – Closed-Loop Wavefront Control

The envisioned wavefront hopping-capable THz wireless system operates in line with the general procedure illustrated in Fig. 1. First, the THz Access Point (THz-AP) and the THz User Equipment (THz-UE) get a set of preloaded THz wavefront (WF) implementations (i.e., codebooks for the phased array, so the implementation is already feasible today by extending the existing beamforming-based architectures [9]) they can operate. Then, both the THz-AP and the THz-UE select the subset of pre-configured wavefronts that can be used to communicate with each other. This is performed by following a procedure similar to that used in 5G NR networks for negotiating a set of frequency channels, modulation schemes, or beamforming configurations to use.

Later, the THz-AP continuously monitors the channel conditions and the performance/reliability of the ongoing data exchange concerning the manifested traffic KPIs. Optionally, the THz-AP can also rely on extra knowledge obtained from network sensing and out-of-band channel information, if available [3]. Based on these data, the envisioned wavefront control mechanism decides if the wavefront needs to be updated for the upcoming X data frames. Once the new WF configuration is selected, the THz-UE also gets updated. In its turn, the THz-UE follows the instructions by the THz-AP while facilitating the intelligent wavefront hopping by both parties sharing the relevant updates.

Below, we study the advantages of the wavefront-capable THz system over the THz radio equipped with only one wavefront and also discuss the research challenges toward the successful implementation of the reviewed concept.

Dynamic Blockage Mitigation with Wavefront Hopping

Inherent Problem of Dynamic Blockage in 5G+ Networks

Highly directional mmWave and (sub-)THz communications bring not only advantages but also challenges. Besides additional difficulties with beam (re-)alignment and mobility tracking, an important inherent problem is blockage. The severity is due to a combination of two main factors: mmWave and THz signals are strongly attenuated (up to 10 dB — 40 dB [3]) when propagating through many typical surfaces (walls, desks, human bodies); and the resulting directional beams are quite narrow in space, so if the main path is blocked, the beam is not wide enough to that is, diffract around the obstacle without losing a substantial part of power.

Existing solutions to address static and dynamic blockage primarily rely on utilizing one of the alternative links via a different AP or RIS (i.e., using *multi-connectivity* [10]). Hence, a greater density of APs is required increasing the costs, as the currently blocked signal path cannot be "healed" in state-of-the-art networks. A better approach is desired for (sub-)THz radio if aiming to support latency- and reliability-stringent services, such as extended Reality (XR).

Mitigating Blockage With Wavefront Hopping

The use of THz wavefront hopping, in contrast, allows to "heal" the link on the fly thus decreasing the negative implications of blockage. Specifically, if the network is capable of sensing the surroundings and predicting a blockage event (which is likely to happen in future networks, as network sensing capabilities are currently under very active development for 6G and beyond [3]), it can then exploit the wavefront hopping technique illustrated in Fig. 2. This figure presents a sketch of operation by a wavefront hopping-capable system to the left side, a non wavefront hopping-capable system to the right, and first-order numerical results comparing the two in the same conditions that are further discussed in the next subsection. Here, an abstract Dt is used to illustrate the time axis.

On the left side of Fig. 2, when a mobile blocker starts occluding the link, the THz-AP dynamically adjusts the wavefront by hopping from a "straight" one (such as Bessel beam) to a curved-trajectory one (i.e., Airy-like), thus bypassing the signal around the blocker. The same approach can be applied to a case, where the THz-UE is moving and the obstacle is stationary (i.e., THz-UE passing a lamppost), or both THz-UE and the blocker move at the same time. This solution addresses not all the blockage events. Specifically, if the THz-UE moves behind a large wall, this technique is not helpful. However, the approach well addresses smaller-scale dynamic blockage by road signs, furniture, and pedestrians, which are the most unpredictable and thus the most harmful.

First-Order Evaluation and Results

To quantify the possible security gains from utilizing THz wavefront hopping, we model a single THz-AP — THz-UE data link and a mobile blocker crossing the line-of-sight. The setup is modeled with a compound COMSOL — Python framework, where all the electromagnetic field modeling is performed in COMSOL for each of the snapshots, while the Python component post-processes the results accounting for the blocker's mobility. The key parameters are given in Table 1. We compare the received power as a function of time for the THz Bessel beam, several THz Airy beams with different curvature parameters, and the THz wavefront hopping over both THz Bessel and THz Airy beams. As illustrated in the middle of Fig. 2, the THz wavefront hopping features the same power as the THz Bessel before and after the blockage event, while outperforming both the Bessel beam and each of the Airy beams by up to 10 dB during the blockage events.

Interference Suppression with Wavefront Hopping

The Problem of Directional Interference in 5G Networks

Highly-directional transmission and reception theoretically decrease the probability of interference events in mobile networks. However, the interference is still non-negligible in many scenarios and the complexity of the associate models to properly account for it increases drastically [11]. Existing mitigation techniques (such as zero-forcing) facilitate suppressing the average negative impact of interference. Still, little can be done if two mobile users get very close to each other and desire to communicate in (almost) the same direction using the same frequency/time resources.

Parameter	Value
Key Radio Parameters (common across all three studies)	
Central frequency	300 GHz
Transmit power, downlink (THz-AP)	20 dBm
THz-AP antenna	30 cm × 30 cm
THz-UE antenna	4 cm × 4 cm
Dynamic blockage	
Communication range (THz-AP to THz-UE)	4 m
THz-AP to blocker distance	2.5 m
Blocker shape	a cylinder
Blocker's diameter	24 cm
Directional interference	
Range (THz-AP1 to THz-UE1)	4 m
Range (THz-AP2 to THz-UE2)	5 m
THz-AP1 to THz-AP2 distance	0.6 m
Physical layer security	
Communication range (THz-AP to THz-UE)	5 m
Number of cooperating attackers	Up to 2
THz wavefronts (key parameters)	
Beamforming Gaussian beam width	20 cm
Airy beam curvature	follows THz-UE
Bessel beam angular width	0.5°
Beamfocusing focal point	at the THz-UE

TABLE 1. Numerical study parameters.

Mitigating Interference With Wavefront Hopping

One of the possible solutions is through wavefront hopping, as illustrated in Fig. 3, where THz-UE2 intentionally hops to a curved-shape wavefront, when the THz-UE1 is passing by. Figure 3 features a layout similar to Fig. 2 above with a wavefront hopping time diagram to the left, non wavefront hopping time diagram to the right, and first-order simulation results in the middle, detailed in the next subsection. As discussed above, the curved-shaped wavefront, concentrates most of the energy (and thus interference) to one side, thus allowing THz-UE2 to pass by with less negative impact.

First-Order Evaluation and Results

To quantify the gains, we model the scenario in Fig. 3 with the parameters from Table 1. For this purpose, a compound Matlab — Python simulation framework is used, where the Matlab component simulates the electromagnetic fields for each of the four propagation paths involved, while the Python component models the mobility of the THz-UE1 and wavefront hopping, as well as calculates the KPIs. We particularly explore beamforming on both links, Bessel beams on both links, Bessel beam on THz-AP1 — THz-UE1 link plus Airy-like curved beam on THz-AP2 — THz-UE2, and also beamforming on THz-AP1 — THz-UE1 plus Airy-like beam on THz-AP2 — THz-UE2 link. The results are also compared to THz wavefront

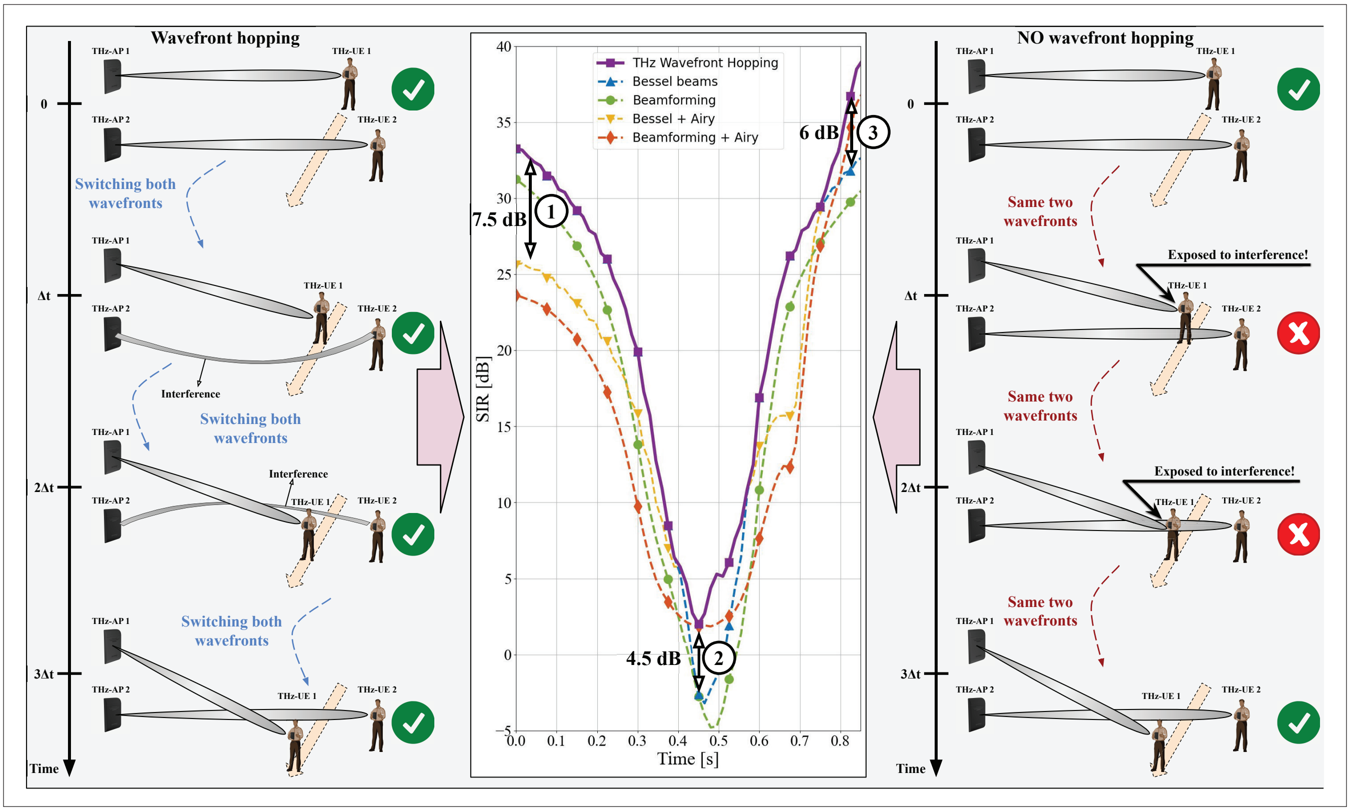

FIGURE 3. THz wavefront hopping to mitigate inter-cell interference. A high-level time diagram of wavefront hopping-capable THz system (left), non wavefront hopping-capable THz system (right), and first-order simulation results in the middle.

hopping, able to dynamically hop to the most suitable wavefront.

As presented in the center of Fig. 3, the average signal-to-interference ratio (SIR) among THz-UE1 and THz-UE2 is non-monotonic in time. It particularly correlates with the mutual location of THz-UE1 and THz-UE2 leading to three key observations. First, for the starting locations, narrow Bessel beams on both links are best and outperform a combination of Bessel + Airy by 7.5 dB. Simultaneously, when THz-UE1 gets closer to THz-UE2 (around 0.5 s), the situation changes and the use of an Airy-like beam with most of the interference pointed in the opposite side brings the SIR up to 4.5 dB and also keeps the average SIR above zero. Finally, the trend continues with another notable advantage of wavefront hopping coming around 0.8 s, where the Bessel + Airy is still over 6 dB better than pure Bessel. Hence, the use of THz wavefront hopping allows to suppress the interference even when the mobile nodes are almost co-located in space and the beams come from almost the same direction.

Physical Layer Security with Wavefront Hopping

Physical Layer Security in 5G and 6G Networks

Securing wireless data exchange already at the physical layer is a tempting feature explored for decades. With the use of highly-directional mmWave and, especially, THz links, this concept becomes practical, as the node outside of the narrow transmitted beam cannot eavesdrop the message. However, it has been shown that even a narrow standalone THz link can be eavesdropped [12], which becomes even more severe in the THz near field, where a beamforming configuration is not fully formed, and the semi-formed beam is much wider in space [6] thus being more vulnerable to eavesdropping. Wavefront hopping provides a more attractive solution.

Physical Layer Security With Wavefront Hopping

The use of THz wavefront hopping allows to alternate different THz wavefronts in the time domain, as illustrated in Fig. 4 that follows the same layout as Figs. 2 and 3. The system to the left side of Fig. 4 alternates transmitting the data using one Bessel beam and two Airy beams in the time domain. Each of the wavefronts carries a part of the message encoded jointly, so it can only be decoded if all the parts are received correctly. With such an approach, a single attacking node can rarely eavesdrop the data exchange. Further, contrary to discussions in [3], no reflections or smart NLoS paths are required due to the utilization of wavefront hopping. Meanwhile, a cooperative group of attackers (i.e., Attacker 1 and Attacker 2 in Fig. 4) still face a challenge, as they have to be located in every possible area the THz wavefront may come from. This de facto means staying close to the THz-UE from several angles, which is very noticeable in practice.

First-Order Evaluation and Results

To quantify the possible security gains from utilizing THz wavefront hopping, we model a THz link between a THz-AP and a THz-UE. The UE has either one or two attackers in proximity aiming to eavesdrop the link. We compare THz beamforming, THz Bessel beam, and THz wavefront hopping. We par-

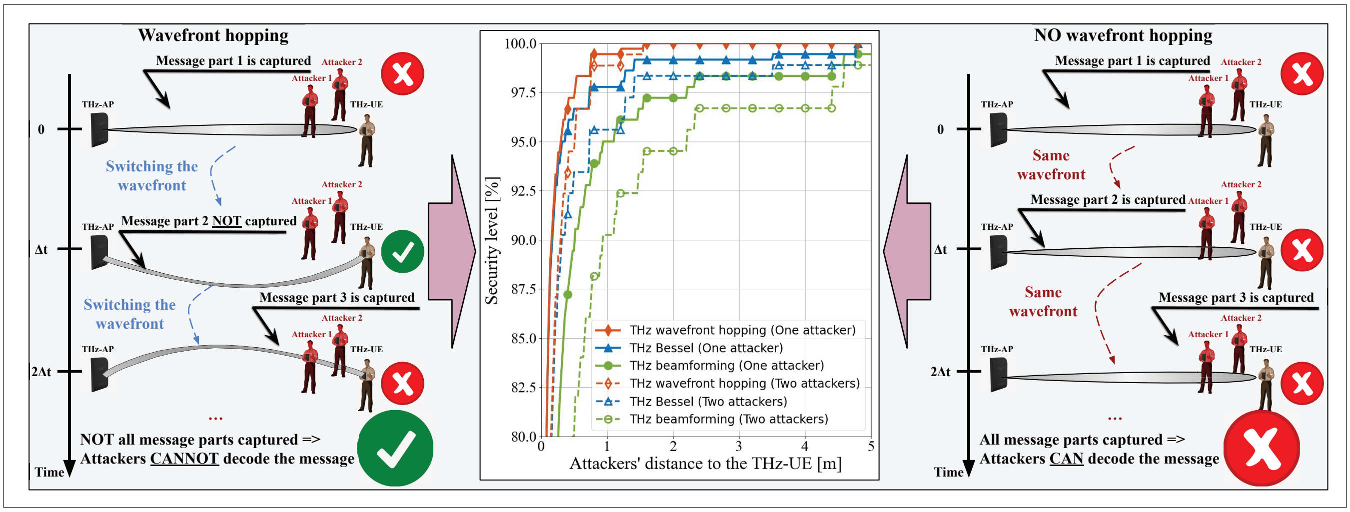

FIGURE 4. Wavefront hopping for physical layer security. A high-level time diagram of wavefront hopping-capable THz system (left), non wavefront hopping-capable THz system (right), and first-order simulation results in the middle.

ticularly focus on the security level of the near-field THz wireless link (probability that the transmitted message cannot be decoded by the attackers) as a function of the proximity between the THz-UE and the attacking nodes. For this security-centric study, we extend the compound Matlab — Python simulation framework used for interference.

As in the center of Fig. 4, the security level naturally grows with the separation distance between the THz-UE and the attackers ultimately reaching 100 percent, that is almost perfect security. Importantly, the use of THz wavefront hopping outperforms both beamforming and Bessel beams decreasing the eavesdropping probability by several times. Also, securing the area of just 1.5 m around the THz-UE allows reaching perfect secrecy with THz wavefront hopping against a single attacker. Hence, the use of wavefront hopping enables the protection of 6G-grade near-field THz links from most eavesdropping attacks. The corresponding areas for existing single-beam solutions are over 5 m in radius, which are much harder to secure.

Toward THz Wavefront Hopping: Research Challenges

Challenge 1: Transmission/Reception of Multiple Wavefronts

While the generation of a given wavefront as discussed earlier is non-trivial [6], hopping amongst the preconfigured wavefronts also imposes its own challenges (Fig. 5). Since wavefront hopping is only at the EM level wherein digital signal processing (DSP) is not required, the entire operation can be simplified by utilizing IRSs collocated with the transmitter and/or receiver, in which programmable elements are utilized that are controlled through a control plane [13]. For example, a large IRS (still small in physical size at THz frequencies) can be subdivided into spatially discrete IRSs, similar to an array of sub-arrays architecture. Each of these sub-IRSs can be pre-programmed for a specific wavefront, and then the choice to be made is which of the sub-arrays to operate. Alternately, the entire IRS can be dynamically switched to a new wavefront.

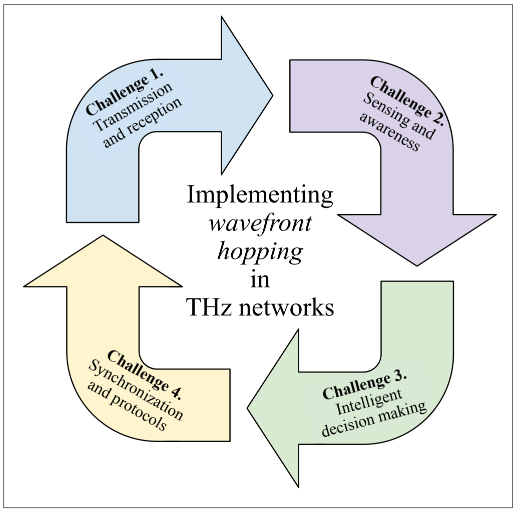

FIGURE 5. Research challenges toward implementing THz wavefront hopping.

At the same time, it is worth noticing that different wavefronts have different propagation characteristics that can affect their performance. For example, the beamsquint effect, extremely large with beamfocusing, can be significantly decreased in Bessel beams by designing these at the lower end of the bandwidth rather than the central carrier frequency. It is also worth remembering that the instantaneous bandwidth of a large array is roughly equivalent to the inverse of the propagation time for a signal across its length. Thus, when the structure is larger, the operable bandwidth of the array can decrease. Here too, off-the-chip metasurfaces and IRSs provide a practical solution, since all the elements can be fed at the same time with the signal, thus preserving the bandwidth requirements. Without the complexity of multiple RF chains, off-chip metasurfaces and IRSs equipped with broadband phase shifters and improved resolution appear to be the ultimate choice in implementing wavefront hopping, providing a perfect combination of size, weight, power, and cost concerns. Thus, the focus of the research community should be to explore this breakthrough.

Thus, the problem of the receiver side, regardless of the device design, should be to capture the received signal with maximum SNR. The task at the receiver is to utilize the array, or the DSP block, as a synthetic aperture, which is perfectly correlated to the incoming wavefront.

Finally, wavefront hopping, as a subset of wavefront engineering, is mostly valid in the context of wavefront generation, or from the standpoint of the transmitter. Nonetheless, the receiver must also be capable of receiving different wavefronts. Thus, the problem of the receiver side, regardless of the device design, should be to capture the received signal with maximum SNR. The task at the receiver is to utilize the array, or the DSP block, as a synthetic aperture, which is perfectly correlated to the incoming wavefront.

Challenge 2: Sensing and Situation Awareness

Designing the radio chip and antenna system capable of switching among several pre-configured wavefronts is only the first step. The next immediate question to address is: "*How to decide which wavefront to use for the next frame or packet?*" To answer this question, next-generation communication systems have to become aware of their surroundings. This starts with the in-band information already available, such as the current traffic category and its KPIs. The next layer of useful data is additional in-band information possible to collect, but not yet accounted for in the existing physical layer, such as the anticipated time of the next packet arrival, among others. Finally, the out-of-band information becomes useful, presenting the knowledge on the current environment around the data link, the trajectory of the THz-UE, and the locations and velocities of key objects around.

The last set of data requires a novel mechanism to collect such kind of information, most likely utilizing one of the approaches today referred to as network sensing. Network sensing is an actively developing research direction kicked off decades ago and is today identified as one of the key candidate features for prospective 6G-grade wireless networks [14]. The key idea is to enhance the communication system with active sensing capabilities, where either some existing communications signals, that is, preambles or synchronization signal blocks, (SSBs), are simultaneously used for sensing purposes. Alternatively, a certain fraction of radio resource blocks get reserved exclusively for custom radar-inspired sequences. The use of network sensing will notably increase the system awareness of the surroundings, which is beneficial for both improving the wireless system performance via adaptation mechanisms, including the discussed wavefront hopping, and novel applications beyond networking (drone detection, etc.).

Challenge 3: Intelligent Decision Making

Even assuming that the communicating node (the THz-AP or the THz-UE) knows *everything* about the environment at the present moment (which is rarely feasible), this is still not sufficient without the next element — intelligent decision-making. The prospective THz radio systems implementing wavefront hopping must become capable of processing the available (realistically, partial) information about the channel, traffic, KPIs, other nodes' locations, and intelligently select the most appropriate THz wavefront for the next group of frames. This is needed to design both reactive mechanisms (i.e., detecting the blockage event by not receiving multiple acknowledgments and adjusting the wavefront accordingly) or, ideally, proactive solutions (envisioning the blockage event to happen soon and hopping the wavefront in advance).

In contrast to existing rate control mechanisms that typically take into account only a few parameters, the intelligence for wavefront hopping has to operate with a large volume of heterogeneous data (both in-band and out-of-band, if available). Hence, designing an efficient intelligence for wavefront hopping is a non-trivial research challenge. Here, the suitability of hardware-accelerated artificial intelligence and machine learning algorithms should be particularly studied among other approaches [15]. This imposes a novel set of research questions for both the software level — what kind of algorithm/learning model suits best — and the hardware level — how to seamlessly and efficiently pair that is, multicore neural engines or similar computing units with prospective THz transceivers.

Challenge 4: Synchronization and Protocols

The successful implementation of wavefront hopping requires the design and tailoring of novel protocols to maintain tight synchronization between the communicating nodes. First, the THz-AP and the THz-UE should become capable of adjusting their wavefront synchronously, so the transmitted signal has the highest chance of getting received and decoded successfully. Here, as discussed earlier, a closed-loop control protocol is envisioned stemming from the existing rate adaptation mechanisms in 5G NR and/or IEEE 802.11. Second, a synchronization among co-located THz-APs is needed for interference management. Here, one of the closest baselines to start with may be a group of dynamic frequency selection approaches, implemented originally for the IEEE 802.11h and evolving since then. Other approaches are also possible. The critical element is the availability of a low-latency link connecting the co-located THz-APs through a minimal number of hops.

Challenges and Opportunities With Wavefront Hopping

The *key research question to address for the envisioned THz wavefront hopping is identifying the set of practical solutions that brings more benefits than overheads*.

Particularly, operating with multiple wavefronts demands specific hardware discussed in Challenge 1. The network sensing functionality outlined in Challenge 2 does not come for granted. The learning-based optimization techniques from Challenge 3 lead to extra power consumption, while the additional signaling for synchronization (Challenge 4) occupies a certain fraction of radio resources.

The use of wavefront hopping also calls for updates in other mechanisms. For instance, the effect of the currently used wavefront has to be properly compensated for when performing the channel estimation, especially for wideband THz channels. Further, the use of wavefront hopping in multiple-input multiple-output (MIMO) THz systems calls for a joint design of phase matrices to apply. If the next-generation THz network gets equipped with standalone IRSs (e.g., on walls, etc.), they need to be designed in mind for these wavefronts to steer them without corrupting the signal.

Hence, designing the most suitable solutions that keep the latency under the desired limit and the overall performance gain positive is a primary research question. Still, as illustrated earlier, there is likely a group of deployment configurations, where the use of THz wavefront hopping improves the performance without densifying the THz network. Hence, wavefront hopping can even be used to slightly decrease the density of THz-APs while maintaining the desired network performance.

Conclusion

This article discusses THz wavefront hopping — the concept suggesting that instead of hardcoding the most appropriate THz wavefront for a given scenario (such as mobile cellular systems), allowing transceivers to dynamically hop (switch) among several pre-configured THz wavefronts, similar to how modulation is currently adjusted by rate control mechanisms. While the concept suits well the envisioned properties of next-generation mobile THz wireless links, similar solutions can also be explored for other bands in, for example, mmWave and optical frequencies in future research work on 6G and beyond.

There is a long way forward to implement this approach with multiple open questions and research challenges on the way. Hence, some of the presented ideas may not even get implemented within the 6G timeline, but rather stay as work-in-progress until beyond-6G comes to stage. However, THz wavefront hopping is shown to be an extremely powerful technique with the potential to address some of the fundamental limitations of THz wireless networks. Therefore, adding this novel capability on top of existing power, rate (modulation and coding), and frequency adaptation techniques is a promising approach worth further exploring as a research direction toward making prospective mobile THz near-field communications reliable and secure.

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