DIRECTIONAL TERAHERTZ COMMUNICATION SYSTEMS FOR 6G: FACT CHECK

A Quantitative Look

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Sustaining a flexible and ubiquitously available high-data-rate (high-DR) network that is capable of supporting a massive number of end users demands the exploitation of higher-frequency bands, such as the terahertz band (0.1–10 THz). However, the utilization of terahertz wireless systems comes with a number of challenges, many of them associated with the very high propagation losses of terahertz signals, which require the utilization of high-gain directional antennas with strict beam alignment requirements as well as the low signal penetration of (sub)millimeter waves, which leads to intermittent blockage and shadow areas.

In this article, a quantitative discussion of these phenomena and their implications in both backhaul and fronthaul applications of the terahertz spectrum is provided. Starting from state-of-the-art demonstrated terahertz technology parameters, the directivity requirements, impact of beam misalignment, and opportunities for multihop relaying in two different application scenarios are described. For the same conditions, the impact of blockage is quantified, and the benefits of reconfigurable intelligent surfaces

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(RISs) are studied. Finally, the implications of blockage on the physical-layer security of terahertz systems are presented.

The Terahertz Spectrum

As 5G cellular systems continue to be commercially deployed, discussions about the next generation of wireless systems arise. Beyond-5G and 6G networks are expected to deliver substantial performance enhancements, including DRs on the order of terabits per second, while supporting a massive number of end users with diverse application requirements. Today, all of the commercial wireless systems operate in the spectrum under 100 GHz, where the large contiguous bandwidths needed to meet the aforementioned target performance metrics do not exist.

To counterbalance the spectrum scarcity problem, the wireless community has opened the gate to the (sub)terahertz spectrum (from 100 to 10 THz) [1], where large contiguous bandwidths in excess of 100 GHz are available, anticipating that this frequency band will become the key enabler of innovative applications in both fronthaul and backhaul scenarios. While the terahertz spectrum has been largely unexplored by the wireless communications community, there are many scientific applications, including radio astronomy and Earth exploration satellite services, that have been exploiting frequencies above 100 GHz for decades [2]. While regulations for the coexistence of commercial and scientific users of the spectrum above 100 GHz limit the contiguous bandwidth, there are plenty of resources to enable 6G systems.

The Role of Terahertz Communications in the 6G Era

The exploitation of the terahertz band will become a catalyst of 6G applications (see Figure 1), which can be grouped as wireless backhaul, fronthaul, and integrated backhaul and fronthaul applications. Different uses have varying requirements that drastically influence the system design, as we discuss next.

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Backhauling

The scenario of fixed backhauling through a wireless fiber extender aims to provide reliable communication with very high DRs (in excess of 100 Gb/s) at long distances (up to a few kilometers) in adverse geographies, such as rivers and dams, or in environments where civil work construction is not allowed due to regulatory constraints. Currently, rural users suffer low connectivity, but the 6G vision aspires to guarantee the high availability of DRs of at least 10 Gb/s/user. The wireless fiber extender has a low-complexity setup, high flexibility, and low total cost of ownership when compared to the fiber deployment. However, the need for very-high-gain directional antennas to enable such long-range links requires precise beam alignment at all times.

Mobile Ad Hoc Backhauling

Moving nodes, such as nomadic base stations can serve as access points that offer backhaul solutions for ultrahigh-DR connectivity (in excess of 10 Gb/s) over comparatively shorter distances than fixed backhaul (up to hundreds of meters) in cases of irregular traffic increase, ultradense connectivity demands, and mobile environments. Mobile ad hoc backhauls can enable and support point-to-point, point-to-multipoint, and mesh architectures with multihop connectivity in outdoor scenarios, including campuses, outdoor shopping malls, and within towns and cities, among others. In addition to the need for a high-gain directional antenna and, thus, precise beam alignment, similar to fixed backhaul applications, the mobility of both the network nodes and the users of the network can lead to blockage and frequent disconnects.

Fronthauling

The utilization of terahertz links in the fronthaul is expected to support DR-hungry applications (peak DRs approaching 1 Tb/s) and a massive number of end users with large aggregated demands grouped in small cells. While terahertz radios today do not meet the size, weight, and power requirements of mobile handsets, major progress is being conducted to overcome this limitation [3]. As with mobile ad hoc backhaul, beam misalignment and intermittent blockage resulting from mobility in this use case are the major challenges to overcome. Moreover, in the majority of indoor and some

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outdoor scenarios, the fact that terahertz signals do not propagate well through many of the building materials requires the utilization of additional network infrastructure in the form of RISs [4] to engineer the propagation of signals.

Integrated Access and Backhaul

Following the trends of the cellular industry, integrated access and backhaul (IAB) at terahertz frequencies are also possible. Two options for backhaul/fronthaul wireless connectivity exist, namely, terahertz–microwave [5] and all terahertz [6]. In the terahertz–microwave case, a terahertz system is utilized to carry aggregated microwave/millimeter-wave links, and, thus, the major challenges are similar to those of only backhaul services for terahertz. Instead, an all-terahertz IAB system combines the challenges of both terahertz backhaul and fronthaul, but it also opens the door to simplified hardware architectures and the possibility to dynamically adapt or trade resources between fronthaul and backhaul services.

Motivation and Contribution

In all of the aforementioned applications, there are three recurring challenges: the need for very-high-gain directional antennas to establish high-bandwidth/-DR links over meaningful distances, the strict beam alignment constraints that these impose on the transmitters (Txs) and receivers (Rxs), and the role of blockage at terahertz frequencies. While these issues have been discussed before, an actual quantitative analysis taking into account realistic technology parameters and deployment scenarios is missing. That is the goal of this article.

Terahertz Directivity and Beam Misalignment

How Much Directivity Is Needed?

The technology-imposed limitations on the transmission power of terahertz transceivers (on the order of 1 mW

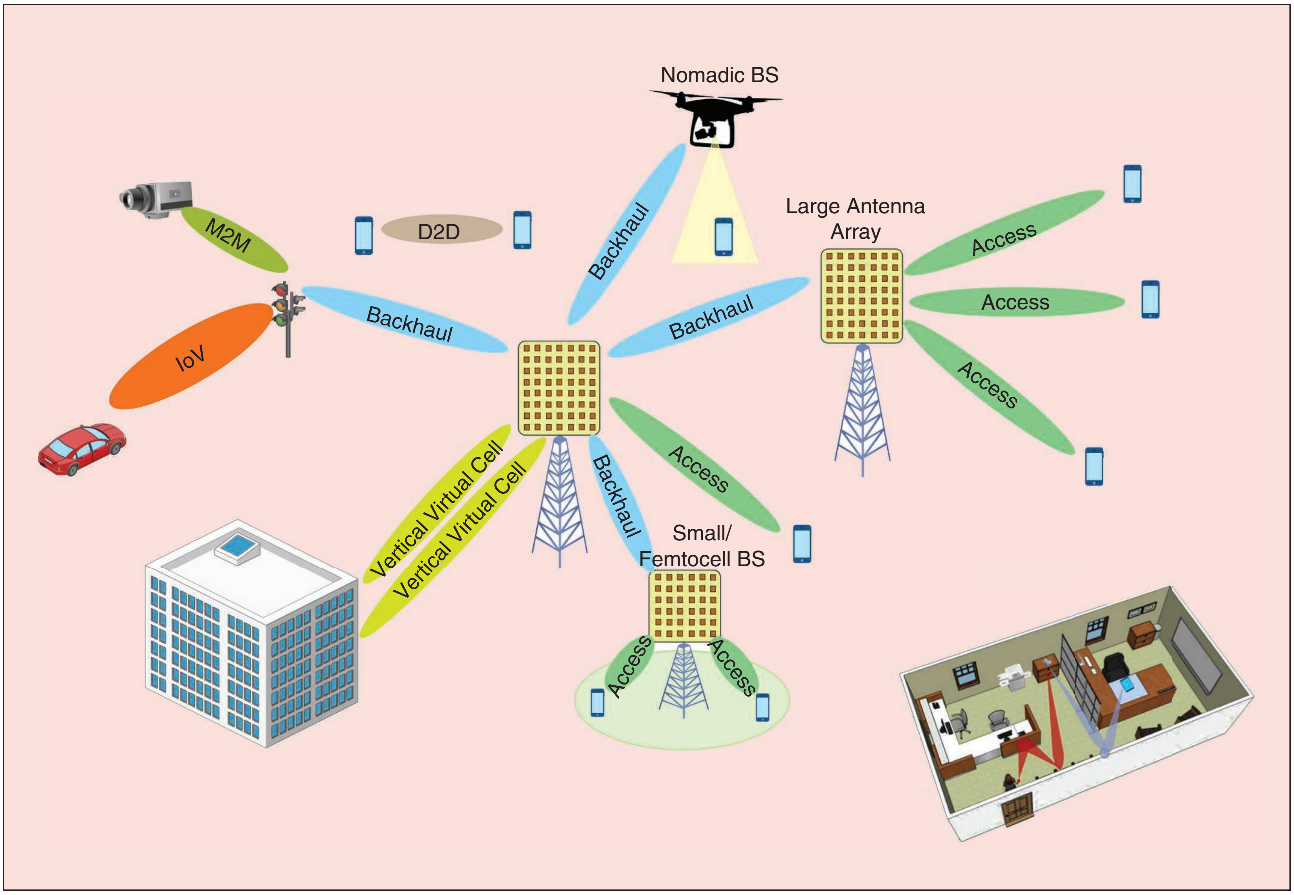

FIGURE 1 The key application scenarios of terahertz wireless systems in the 6G era. Light green, blue, orange, and dark green represent the vertical virtual cell, backhaul, Internet of Vehicle Access (IoV), machine-to-machine (M2M), and access links, respectively. BS: base station; D2D: device to device.

when utilizing established CMOS technologies and up to a few hundred milliwatts when adopting III–V semiconductor technologies [3]) combined with the high propagation losses at terahertz frequencies (resulting mostly from the small effective area of terahertz antennas when operating within the molecular absorption free bands of the spectrum above 100 GHz [7]) require the utilization of high-gain directional antennas simultaneously at the Tx and Rx of a terahertz communication link. Usually, in the literature, such antennas are assumed to be static, and the problem is mostly in acquiring the correct direction to maximize the antenna gain.

However, sustaining perfectly aligned Tx and Rx antennas in practical scenarios is not always feasible. In more detail, as reported in [8], in terahertz wireless fiber extender scenarios, thermal expansion, dynamic wind loads, weak earthquakes, and other physical phenomena cause vibrations of the transceiver antennas that are placed in high-rise buildings and lead to beam misalignment. On the other hand, in fronthaul scenarios, estimation errors in the angle of arrival or departure; user micromobility patterns; and imperfection in the antenna array, which includes array perturbation and mutual coupling, cause stochastic tracking estimation errors.

To quantify the impact of beam misalignment on the transmission distance of wireless terahertz systems, in Figure 2, we plot the maximum achievable transmission distance that ensures an uncoded bit error rate (BER) of 10^{-6} as a function of the antenna gain for different values of the beam misalignment standard deviation σ, assuming that both transceivers are equipped with the same type of antenna. Two indicative scenarios are examined.

In both scenarios, the transmission frequency is set to 287.28 GHz. The bandwidth and transmission power in the first scenario are, respectively, 10 GHz and 10 dBm, whereas these are set to 100 GHz and 20 dBm in the second scenario. In both scenarios, III–V semiconductor Txs, able to support more than 20 dBm of transmission power, are considered. The propagation losses are computed utilizing the channel model given in [7]. At the Rx, the mixer conversion and miscellaneous losses are set to 8 and 5 dB, respectively, whereas the mixer and low-noise amplifier (LNA) noise figures are 6 and 1 dB, respectively. Additionally, the LNA gain is 25 dB.

FOLLOWING THE TRENDS OF THE CELLULAR INDUSTRY, INTEGRATED ACCESS AND BACKHAUL AT TERAHERTZ FREQUENCIES ARE ALSO POSSIBLE.

All of these values are in alignment with state-of-the-art experimental terahertz communication platforms, such as those developed by our team [9]. Moreover, note that, in realistic terahertz wireless systems that are used for wireless access or device-to-device communications, the antenna gain of mobile devices is not expected to surpass 35 dBi. On the other hand, in backhauling, implementations that have employed even 55-dBi

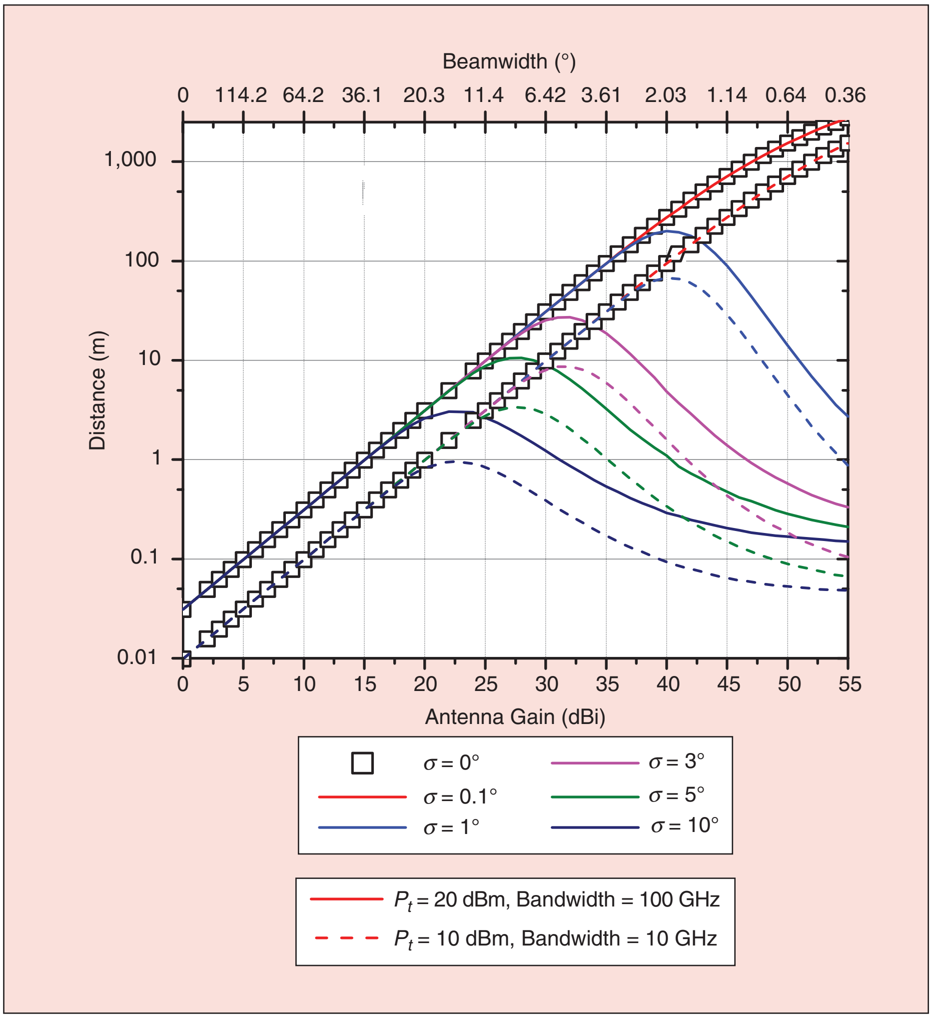

FIGURE 2 The maximum achievable transmission distance as a function of the Tx antenna gains for two indicative application scenarios and values of beam misalignment standard deviations.

SUSTAINING PERFECTLY ALIGNED TX AND RX ANTENNAS IN PRACTICAL SCENARIOS IS NOT ALWAYS FEASIBLE.

Cassegrain antennas have been reported (see, e.g., [8] and the references therein). (It is worth noting that the design of 25–55-dBi compact antennas as well as power amplifiers capable of supporting 100-GHz bandwidth is currently under investigation.)

Finally, according to [10], the beam misalignment depends on the accuracy capabilities of the beam-tracking algorithm in mobile wireless environments as well as physical phenomena, such as small earthquakes and/or wind, and can even reach 180°. For brevity, all of the simulation parameters are summarized in Table 1.

When a quaternary phase-shift keying (QPSK) modulation scheme is employed, the achievable DRs in the first and second scenarios are, respectively, 20 and 200 Gb/s. The first setup may support an augmented/virtual reality (AR/VR) application, while the second is suitable for backhauling. As a benchmark, the ideal case in which there is no misalignment between the Tx and Rx is also presented. From this figure, we observe that, in the absence of misalignment, for a given scenario, as the antenna gain increases, the achievable transmission distance also increases, as expected. For example, for backhauling, as the antenna gain increases from 25 to 55 dBi, the transmission distance changes from 10 m to 2 km.

However, in the presence of beam misalignment, we observe that there exists a specific antenna gain up to which, as the antenna gain increases, the transmission distance also increases. Beyond this value, as antenna gain increases, the maximum transmission distance decreases. In other words, it is observed that there exists an optimal antenna gain that approximately corresponds to an antenna beamwidth that is 1.5 times the misalignment standard deviation σ.

For example, for backhauling and $\sigma = 10^{\circ}$, the optimal antenna gain is 22 dB, which corresponds to a beamwidth of 15° and achieves a maximum transmission distance of 1 m, while, for $\sigma = 1^{\circ}$, which corresponds to a beamwidth of 1.5°, the maximum transmission distance that can be achieved is 250 m. This highlights the importance of taking into account beam misalignment when evaluating the link budget of terahertz wireless systems and selecting their transmission characteristics.

TABLE 1 The simulation parameters.

Parameters	Scenario 1 (AR/VR Fronthauling)	Scenario 2 (Backhauling)
Uncoded BER	10^{-6}	
Required DR, Gb/s	20	200
Modulation	QPSK	
Bandwidth, GHz	10	100
Tx power, dBm	10	20
Tx frequency, GHz	287.28	
Rx mixer convention loss, dB	8	
Rx miscellaneous loss, dB	5	
LNA gain, dB	25	
Rx mixer noise figure, dB	6	
LNA noise figure, dB	1	

AR/VR: augmented/virtual reality; QPSK: quaternary phase-shift keying.

How to Overcome Misalignment

A beam misalignment mitigation approach that has been investigated in the open literature is the use of relaying protocols. In [11], we presented an opportunistic relaying strategy to moderate the impact of beam misalignment. In Figure 3, we illustrate the maximum achievable transmission distance as a function of the antenna gain for different values of the beam misalignment standard deviation σ for the AR/VR application. Again, two scenarios are examined.

In the first one, the source (S) communicates with the destination (D) through an amplify-and-forward relay. As depicted in Figure 3(b), it is assumed that the relay is located in the middle of the S–D path. In the second scenario, two amplify-and-forward relays are placed in the middle of the S and D. In each transmission cycle, the relay that minimizes the influence of the beam misalignment is selected. In both scenarios, it is assumed that both transceivers are equipped with the same type of antenna. For the sake of comparison, the total transmission powers and achievable DRs of the first and second systems are assumed to be equal. As a benchmark, the ideal case, in which no beam misalignment exists, is plotted for both systems.

From this figure, we observe that, for the ideal case, as the antenna gain increases, the transmission range also increases. In the case in which beam misalignment exists, up to a specific point, as the antenna gain increases, the transmission range also increases. Beyond this point, an antenna gain increase causes transmission range degradation. Additionally, it becomes apparent that, for a fixed σ, as the number of relays increases, the diversity order increases; thus, the average power loss due to misalignment decreases, and, in turn, the maximum achievable transmission distance increases. For example, for $\sigma = 5^{\circ}$, the maximum achievable transmission distance increases from approximately 10 to 20 m as the number of relays increases from one to two.

Moreover, by comparing the results presented in this figure with the corresponding ones in Figure 2, we observe that, under the same DR, power consumption, and antenna gain specifications, the use of a relay can significantly increase the maximum transmission distance. Finally, it becomes evident that, even if we employ multiple relays, we cannot fully mitigate the impact of beam misalignment.

To counterbalance beam misalignment, accurate channel estimation is required. However, in mobile wireless environments, the variation of terahertz beamspace channels are fast; thus, conventional channel estimation approaches may generate an unaffordable pilot overhead. As a consequence, beam-tracking schemes that exploit the temporal correlation of the terahertz channels have been widely adopted.

Three types of such approaches have been presented in the technical literature. The first one is based on modeling the time-varying channels in concurrent time slots as a Markov process of order one and employing a conventional Kalman filter to estimate the channel variation with reduced overhead [12]. Although this approach has been extensively used in microwave wireless systems, it cannot straightforwardly be applied in terahertz ones due to the sparse nature of the terahertz channel, which cannot be captured by a one-order Markov model.

The fundamental idea behind the second type is to search in a set of possible Tx and Rx beam pairs following a beam-training procedure [13]. This approach has been used in millimeter and terahertz wireless systems. However, it comes with a limitation. It is designed for point-to-point systems, and it cannot be

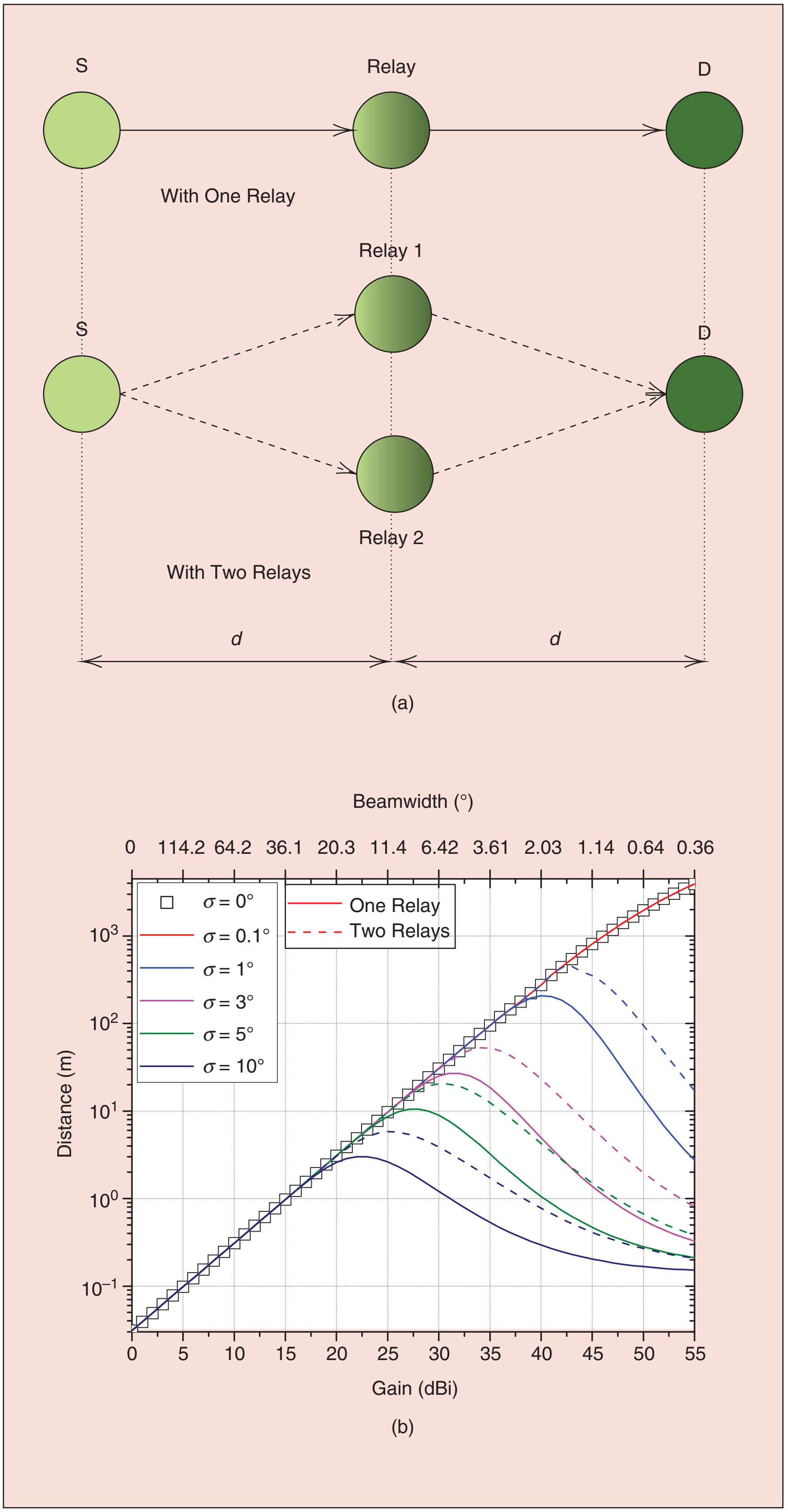

FIGURE 3 (a) The system models. (b) The maximum achievable transmission distance as a function of the Tx antenna gains for two indicative application scenarios and values of beam misalignment standard deviations.

> *THE NEED FOR HIGH-GAIN DIRECTIONAL ANTENNAS SIMULTANEOUSLY AT THE TX AND RX MAKES TERAHERTZ WAVES DIFFICULT TO INTERCEPT.*

easily extended in multiuser scenarios. As a result, it is suitable for backhauling use cases.

Finally, the last type is based on prior-assisted beam tracking by means of user motion prediction [14]. This approach can support multiuser scenarios, and, thus, it is suitable for fronthauling use cases. Despite the paramount interest of the last approach, there are only limited contributions that look at it. This motivates investigations in this direction and opens the road for presenting machine learning-based methodologies for predicting user motion.

Blockage and the Role of RISs Above 100 GHz

What Is the Blockage Probability?

In addition to high propagation losses, terahertz signals can be obstructed (i.e., absorbed, reflected, or diffracted) by different types of obstacles (from people and furniture to walls, windows, and trees). In Figure 4, we illustrate an example scenario consisting of a Tx, an Rx at 10 m, and an obstacle of radius 0.5 m in a 10-by-10-m room. To compute the received signal strength across a 2D cut of this geometry, we utilize the same system parameters as in Table 1 (AR/VR), i.e., the signal bandwidth and transmission power are, respectively, 10 GHz and 10 dBm. We set the Tx and Rx antenna gains to 30 dBi, which approximately corresponds to a beamwidth of 3.61°. This could be achieved, for example, with a 13×13 planar patch antenna array with less than a 1-cm^2 footprint thanks to the very small wavelength at the design transmission frequency.

The figure is to scale, which highlights the fact that the beams are very narrow. The impact of obstructing obstacles is twofold. On the one hand, they create a shadow area, which might (partially) block the Rx antenna effective area. On the other hand, the obstacle itself might reflect the signal, absorb it, or do both. In this section, we focus on the impact of the shadowing and, thus, blockage of the signal at the Rx. In the "Impact of Beamwidth and Bandwidth on Physical-Layer Security" section, we discuss instead the impact of reflections.

In Figure 5, we illustrate the probability density function (PDF) of the blockage percentage for a specific scenario with the same geometry as in Figure 4 but with five obstacles randomly positioned within the room. The PDF is estimated by normalizing the histogram of 10,000 realizations. Despite its simplicity, this figure highlights different features of blockage in directional terahertz systems. In particular, while partial blockage is possible, i.e., the probability of blockage larger than 0% and smaller than 100% is not always zero in our extensive numerical study, blockage can be generally modeled as a binary process and, thus, represented with a Bernoulli distribution. The binary nature of blockage shown by this numerical analysis is well aligned with the experimental measurements reported as part of the study in [15]. In addition to its relative position, the specific blocking probability largely depends on the type of obstacle and its size.

How Much Can RISs Improve Connectivity?

As with lower-frequency systems, terahertz RISs [4] are capable of creating alternative paths between the S and D; thus, they are considered an attractive

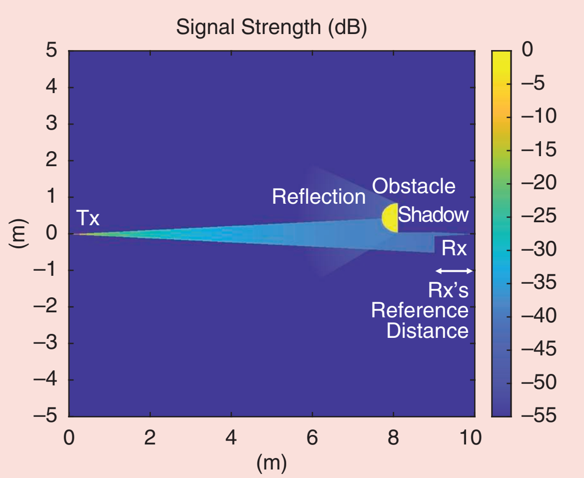

FIGURE 4 A heat map in the example scenario consisting of one Tx, one Rx, and an obstacle.

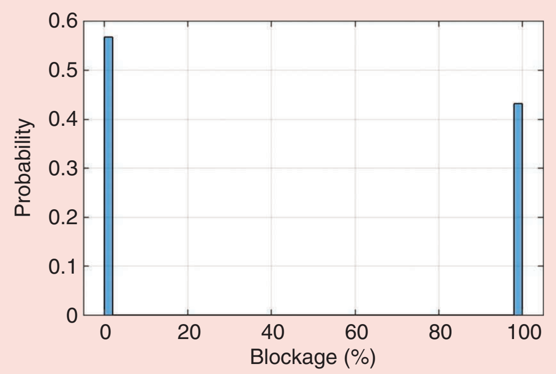

FIGURE 5 The probability density function of the blockage percentage for a scenario such as that given in Figure 4 with five randomly positioned obstacles.

solution for the blockage problem. To quantify the performance of RIS-assisted terahertz wireless systems in the presence of multiple blockers, we continue with our previous example and consider an RIS-assisted terahertz wireless system operating in a room, such as that of Figure 4.

We use circular disks of different radii to model blockers. The radius is a uniform random variable with a mean of 0.5 m. The blockers' positions are returned by a point Poisson process, in which density is selected to achieve a predetermined ratio of blocker-covered to total network area. We define a 2D Cartesian coordinate system in which the $O(0, 0)$ is set at the left bottom corner, while the x- and y-axes are parallel to the underside and left side of the room, respectively. The S node is located at $O(0, 0)$, while the RIS is at $R(5\text{ m}, 10\text{ m})$. Additionally, D is at distance d_{SD} from S and d_{RD} from the RIS. Finally, the S–RIS–D angle is set to 60°.

Figure 6 depicts the blockage probability as a function of d_{SR} and d_{SD} for three different scenarios: 1) direct connectivity between S and D, 2) S–RIS–D connectivity, and 3) opportunistic connectivity, assuming that the fraction covered by blockers is 10% and 50%. For all of the aforementioned scenarios, for a given blocker's coverage fraction, we observe that, as the end-to-end S–D distance increases, the blocking probability increases. Moreover, for fixed d_{RD} and d_{SD}, as the fraction covered by the blocker's area increases, the blocking probability increases.

Also, from this figure, it becomes evident that, for cases of both direct and S–RIS–D connectivity, the blocking probability is more than 10^{-2}, which is unacceptable for AR/VR applications. However, by creating an opportunistic strategy, based on which the unblocked link is selected, we can considerably reduce the blocking probability. Finally, it is highlighted that, even when the opportunistic strategy is employed, in scenarios with a high fraction covered by the blocker area, a blocking probability that is lower than 10^{-3} cannot be guaranteed.

Impact of Beamwidth and Bandwidth on Physical-Layer Security

How Secure Are Terahertz Communication Systems?

The need for high-gain directional antennas simultaneously at the Tx and Rx makes terahertz waves difficult to intercept. For an eavesdropper to successfully intercept a terahertz signal, he or she needs to be positioned within the very narrow beam of the Tx while utilizing a very narrow beam itself. As with any other terahertz link, beam discovery and tracking would be necessary, and these are much more challenging in the (expected) lack of cooperation between the Tx and eavesdropper.

The fact that these systems can operate today is the result of years of research across hardware, propagation, and the physical layer.

Nevertheless, as first discussed in [15], it is still possible to intercept terahertz signals by leveraging the physics of electromagnetic (EM) waves. Let us consider a scenario with a Tx (Alice), a legitimate Rx (Bob), and an eavesdropper (Eve). For Eve to be able to intercept an ongoing transmission, first and foremost, she needs to know the locations of both Alice and Bob and the orientations of their antennas.

Discovering neighboring nodes is not an easy task at millimeter-wave and terahertz frequencies, and it becomes even more challenging when there is no coordination between the nodes that need to be discovered. Under the assumption that Eve indeed knows the position and orientation of Alice's antenna beam, it was shown in [15] that, as with any other form of EM radiation at any frequency (both lower microwave and higher optical frequencies), a highly reflective (e.g., metallic) obstacle could be introduced to (partially) reflect or diffract a portion of the EM signal off the path between the Alice and Bob.

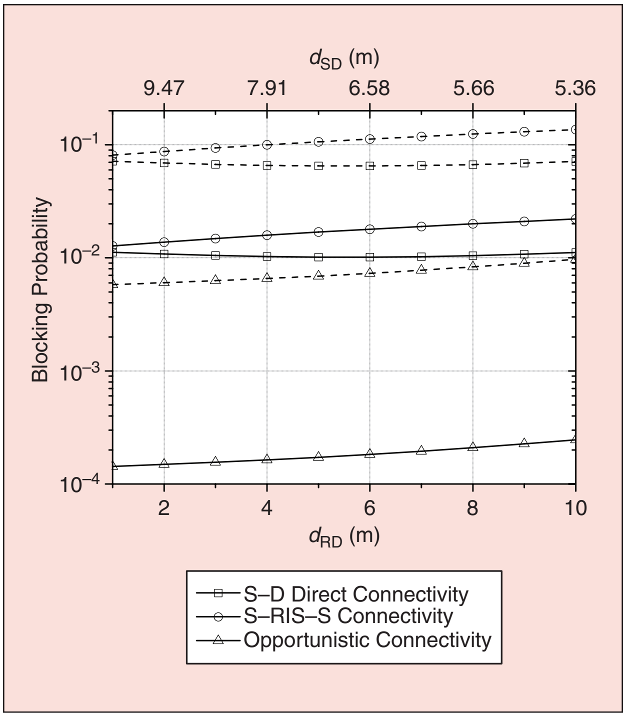

FIGURE 6 The blocking probability versus RIS–D distance for three different scenarios: the 1) direct connectivity between S and D, 2) S–RIS–D connectivity, and 3) opportunistic connectivity, assuming that the fraction covered by the blocker area is 10% (continuous lines) and 50% (dashed lines).

DISCOVERING NEIGHBORING NODES IS NOT AN EASY TASK AT MILLIMETER-WAVE AND TERAHERTZ FREQUENCIES.

The small wavelength of the terahertz waves (the same property that allows for the development of compact high-gain directional antennas and antenna arrays) also leads to the fact that even a very small metallic obstacle (e.g., a paper clip) can create a strong enough replica. Therefore, beyond intermittent connectivity problems between users, as discussed in the previous section, blockage can also open the door to eavesdropping.

To quantitatively analyze this phenomenon, building on our results in [15] and extending the study to scenarios with multiple obstacles for the first time, in Figure 7, we illustrate the PDF of the information capacity theoretically achievable by Eve for the same Scenario 1 as in the previous sections. In these results, we consider different combinations of the number (5, 10, or 15) and radius (0.1 or 0.5 m) of highly reflective obstacles, randomly distributed within a 10 × 10-m area.

As before, the signal strength along the path between Alice and Bob was computed based on the assumptions presented in the "Terahertz Directivity and Beam Misalignment" section. The blockage (if any) was computed as in the "Impact of Beamwidth and Bandwidth on Physical-Layer Security" section. The reflection of the obstacles was calculated by following our same experimentally validated methodology as in [15]. We consider a worst-case scenario in which Eve can position herself at the point in space outside the main beam where the reflected signal strength is higher. For each set of parameters, 10,000 realizations were conducted.

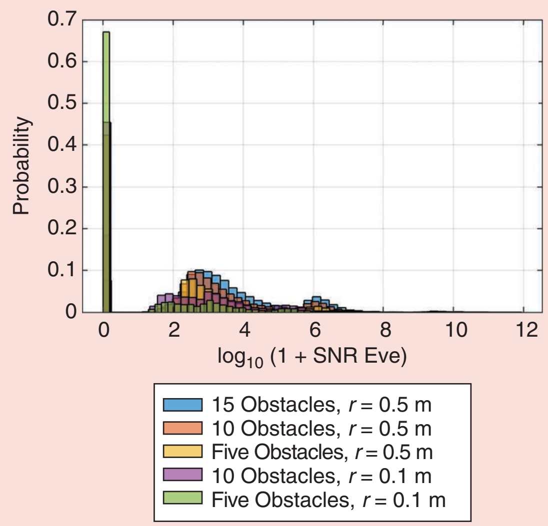

FIGURE 7 The PDF of an agile eavesdropper's information capacity for different obstacle configurations. SNR: signal-to-noise ratio.

From the results, it can be observed that, when the main path is (partially) blocked, Eve can recover a meaningful copy of the signal (potentially even stronger than that reaching the Rx). In combination with the results in the "Blockage and the Role of RISs Above 100 GHz" section, it is evident that even a small blockage can lead to drastic drops in the signal strength at the Rx. Thus, such a phenomenon is easily detectable by Bob, and, ultimately, either through the lack of feedback or measurement of any reflected signal, Alice can understand the situation and abort communication.

Exploiting the Excess Bandwidth to Secure Terahertz Systems

While the focus of this article is on the implications of directional systems, there are other physics-enabled opportunities to secure terahertz communications. In particular, the very large bandwidth available at terahertz frequencies can also enhance the security of communication systems. First and foremost, synchronizations in time, frequency, and phase at terahertz frequencies are extremely challenging tasks, and, once again, these becomes more complicated in the absence of coordination between users.

Simply stated, intercepting and successfully recovering a message transmitted at tens of gigabits per second is not a trivial task. Beyond this, even when supporting gigabits per second, the excess of channel bandwidth can be leveraged to support spread-spectrum communication techniques, including the direct-sequence spread spectrum, frequency hopping, and the chirp spread spectrum, which, beyond commercial applications, have been popular in military and defense scenarios and, now for the first time, can be leveraged while supporting multigigabit-per-second links.

Conclusions

Building on the state of the art in experimental directional terahertz systems, we have quantitatively derived realistic values for the needed directivity to establish ultrabroadband communication links at terahertz frequencies in both backhaul and fronthaul scenarios, studied the impact of misalignment on the practical link distances, investigated the benefits of incorporating RISs as a way to overcome blockage, and explored the implications on the physical-layer security of terahertz networks. Contrary to some popular beliefs, terahertz links over tens and hundreds of meters (and, in some cases, a few kilometers) are possible today with practical antenna gains, even in the presence of misalignment. Further increasing the distance will require multihop relaying.

Blockage is a problem affecting both the connectivity and security of terahertz systems. Providing smartness to the network elements, whether Txs, Rxs, or additional infrastructure, such as RISs, can help to overcome these practical issues. The fact that these systems can operate today is the result of years of research across hardware, propagation, and the physical layer. Similar efforts are needed to, for example, convert massive and ultramassive multiple-input, multiple-output systems from on-paper theorems to experimental and, ultimately, deployable systems. The good news is that we do not need to wait for those to experience some of the benefits of the terahertz band.

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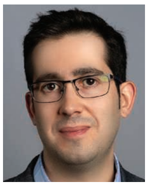

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