Ultra-Massive MIMO Systems at Terahertz Bands: Prospects and Challenges

Alice Faisal, Student Member, IEEE, Hadi Sarieddeen, Member, IEEE, Hayssam Dahrouj, Senior Member, IEEE, Tareq Y. Al-Naffouri, Senior Member, IEEE and Mohamed-Slim Alouini, Fellow, IEEE

Abstract—Terahertz (THz) band communications are currently being celebrated as a key technology that could fulfill the increasing demands for wireless data traffic and higher speed wireless communications. Many challenges, however, have yet to be addressed for this technology to be realized, such as high propagation losses and power limitations, which result in short communication distances. Ultra-massive multiple input multiple output (UM-MIMO) antenna systems have emerged as practical means for combating the distance problem at the THz range; thereby increasing system capacity. Towards that direction, graphene-based nano-antennas of small footprints have been recently proposed, as they can be individually tuned and collectively controlled in an UM-MIMO array of sub-arrays architecture. In this paper, we present a holistic overview of THz UM-MIMO systems by assessing recent advancements in transceiver design and channel modeling. We discuss the major challenges and shortcomings of such designs from a signal processing perspective, by deriving the relation between system performance, communication range, and array dimensions. We further highlight several research advances that could enhance resource allocation at the THz band, including waveform designs, multi-carrier antenna configurations, and spatial modulations. Based on this discussion, we highlight prospect use cases that can bring THz UM-MIMO into reality, in the context of sensing, data centers, and future mid-range wireless communications.

I. INTRODUCTION

TERAHERTZ (THz) band communications promise to exploit the large bandwidths at THz frequencies [1], to fulfill the high data rate demands of future generations of wireless communications. While millimeter wave (mmWave) systems [2] have been extensively explored in recent years over the frequency range of 30 to 300 gigahertz (GHz), the highest attainable bandwidth at such frequencies is 10 GHz, and so a physical layer efficiency of at least 100 bits/sec/Hz is required to achieve a terabit (Tb)/sec data rate. On the contrary, since the available bandwidth between 0.3 THz and 10 THz (i.e., at the THz range) can reach hundreds of GHz, a target Tb/sec data rate can be achieved with minimal physical layer efficiency-enhancement techniques [5].

Over the past few years, affordable technologies have enabled a widespread usage of mmWave systems. For example, mmWave-enabled IEEE 802.11ad (WiFi) networks (WiGig), high-definition (HD) video applications, and single-chip fine-resolution radar integrated circuits have emerged. One of the IEEE 802.15 wireless personal area networks (WPAN) study group’s missions is to explore high-frequency ranges, so as to solve a variety of next-generation wireless communication needs, by supporting multi-gigabit (Gb)/sec and Tb/sec links. Recently, major advancements in transceiver design are closing the so-called THz gap, which paves the way for several applications at the THz band, ranging from indoor wireless communications, to vehicular and drone-to-drone communications, device-to-device (D2D) communications, and nano-communications. THz signals, further, have the potential to be used in many non communication-based applications, such as spectroscopy of small bio-molecules and quality control of pharmaceutical products. The spectrum decomposition and the corresponding applications are illustrated in Fig. 1.

Despite the promising utilization features of THz communications systems, their high-frequency operation properties impose several implementation hurdles, both at the signal generation and at the signal detection levels. Towards addressing such implementation challenges, a variety of integrated electronic and photonic solutions are proposed, that not necessarily result in perfect THz devices, but rather efficient and programmable devices that satisfy emerging system-level properties; see [7] and references therein. Electronics III-V-based semiconductor technologies include Indium Phosphide (InP) heterojunction bipolar transistors (HBTs), high electron mobility transistors (HEMT), and gallium arsenide (GaAs).
based Schottky diodes. At high frequency ranges, however, the corresponding generators and detectors perform poorly at room temperature (plasma waves excited by a HEMT tend to be instable). Photonic solutions, on the other hand, are based on photomixers, difference frequency generation, or parametric generation with nonlinear materials. Quantum cascade lasers (QCLs), which are semiconductor-based pumped lasers consisting of unipolar intersubband transitions, are also used for THz signal generation. Nevertheless, integrated hybrid electronic-photonic systems [2] have been proosed as a deviation from classical approaches.

Recently, plasmonic solutions have emerged as strong candidates that enable communications at the THz band, in particular, graphene-based solutions [3]. The unique electrical properties of graphene, such as high electron mobility, electrical tunability, and configurability, allow supporting high-frequency signals. Plasmonic-based antennas enable the propagation of surface plasmonic polariton (SPP) waves, which are confined electromagnetic (EM) waves that travel through the metal-dielectric interface due to oscillations of electric charges. In fact, SPP waves propagate at speeds that are much lower than those of regular EM waves and, hence, possess a characteristic wavelength (denoted by \( \lambda_{SPP} \)) that is much smaller than the EM wavelength (denoted by \( \lambda \)). Therefore, compact array designs can be deployed, which integrate a massive number of antennas in a tiny footprint [3].

From a coverage perspective, additional crucial challenges still need to be addressed, particularly those related to high propagation losses and power limitations faced at THz frequencies, which result in short communication ranges. To overcome such limitations, we distinguish between either reflect arrays or ultra-massive multiple input multiple output (UM-MIMO) antenna systems, as alternative means to extend the coverage range [3]. UM-MIMO is a more convenient and generic solution than reflect arrays, since the latter is tailored for non line-of-sight (NLoS) environments. UM-MIMO, which is the focus of this paper, offers the valuable advantages of increasing the communication range through beamforming, and improving the achievable data-rate through spatial multiplexing (SMX). In fact, the ability to build compact phase-coherent UM-MIMO arrays (using plasmonic materials such as graphene) is a key added value of THz communications compared to free-space optical (FSO) communications.

The main aim of this paper is to establish a clear link between transceiver design, channel characteristics, and prospect use-cases of THz UM-MIMO systems. Up to our knowledge, the literature lacks a holistic work of this kind. Towards this end, we start by introducing the array of sub-arrays (AoSA) configuration and highlighting the particular advantages for adopting graphene utilization in Sec. II. We then detail various channel modeling approaches in Sec. III so as to best describe the relation between channel characteristics and system performance. We further define open challenges and potential signal-processing research advances in Sec. V which include efficient signal modulation, waveform design, and distance-aware resource allocation. Finally, based on previously discussed constraints, we recommend specific THz UM-MIMO use cases and conclude in sections VI respectively.

II. ARRAY OF SUB-ARRAYS DESIGN

Massive plasmonic antenna configurations are constructed as large arrays of antenna elements (AEs). Since inter-AE separations are typically in the order of \( \lambda \), operating at high frequencies naturally results in dense packaging. For instance, while mmWave AoSAs require footprints of few square centimeters for a small number of antennas, a massive number of antennas can be embedded at THz in a few square millimeters. This densification is further emphasized with plasmonic antennas, where separations are in the order of \( \lambda_{SPP} \) (e.g., \( \lambda_{SPP} = \lambda/15 \) for graphene).

Such compactness in design, however, comes at the cost of limiting the beamforming and multiplexing gains of UM-MIMO, due to inadequate spatial sampling, and increasing the complexity of antenna array control [4]. As a solution, large antenna arrays can be divided into multiple sub-arrays (SAs) of smaller size in an AoSA architecture. Deploying multiple AEs in a SA improves the beamforming gain and decreases the required transmission power for each element. Hence, each SA offers the array gain, and the collaboration between SAs provides the SMX gain. This configuration results in a large number of directed independent paths, each of which can be used to carry independent information, which in turn results in high data capacity. For example, an 18 dB array gain is achieved with a 0.4 mm\(^2\) footprint at 1 THz, using 16 graphene-based SAs, each of which comprises 8 \times 8\) AEs [3].

AoSA architectures were originally proposed for mmWave systems in an indoor environment [5], by investigating the effect of AoSA spacing, the alignment between the transmitting and receiving arrays, and the position of line of sight (LOS) blockage. Reference [6] concludes that SMX gains are more important than beamforming gains for indoor 60 GHz links with typical consuming electronics and computing devices. This is further justified by the fact that beamforming comes at the cost of increased system complexity, where the transmitter requires a perfect knowledge of channel state information for aligning the beam towards the receivers of interest.

Since the energy and spectral efficiencies in an AoSA architecture are dictated by the beamforming strategy, hybrid beamforming is typically sought to reduce hardware costs and power consumption, in which operations get divided between the analog and digital domains. Hybrid AoSA architectures at THz are detailed in [7], where a two-step analog beamforming and user grouping mechanism is illustrated by dividing users according to their angle of departure. Users having the same angle section are first allocated to the same group. Then, each SA carries out beamforming by searching for each user group in the pre-scanned sector. The beamforming angle is selected such that the overall received signal power for one user group over all subcarriers is maximized. Afterwards, digital beamforming is performed in baseband on each subcarrier.

Several other factors have to be taken into consideration in AoSA designs, e.g. the feeding losses due to larger arrays configurations. Furthermore, the mutual coupling effects between adjacent AEs, which depend on the array configuration and the operating frequency, often degrade the system performance (can be neglected for inter-AE separations larger than \( \lambda_{SPP} \)).
III. CHANNEL MODELING AND CHARACTERISTICS

The previous section discusses that UM-MIMO AoSA can combat propagation losses and maximize the achievable gains at the THz band. The exact performance of THz UM-MIMO systems, however, is dictated by the exact channel conditions and the corresponding accuracy in channel state information. In particular, capturing important channel parameters, such as path gain, delay spread, and angular spread allows for efficient exploitation of important channel characteristics, such as spatial degrees of freedom and capacity. The spatial degrees of freedom dictate the maximum SMX gain that can be supported, which is directly linked to channel capacity.

Accurate channel models are thus a prerequisite for efficient utilization of the THz band. Such models should take into account the impact of both spreading and molecular absorption losses. Furthermore, line-of-sight (LoS), NLoS, reflected, and scattered paths should be considered, and static and time-varying environments should be treated separately. Note that realistic channel measurements have been recently reported, such as in [7], where a 140 GHz channel sounder was tailored for both long distance propagation measurements with delay spread, and short range dynamic channel measurements. In what follows, we review several channel modeling approaches and we detail the peculiar characteristics of the THz channel.

A. THz Channel Modelling

THz channel modeling approaches are deterministic, statistical, or hybrid [9]. Deterministic channel modeling depends on site geometry, and is often achieved via ray tracing (RT) techniques that are capable of handling site-specific structures. Applying RT to every channel path, however, increases system complexity. As a solution, point to point RT can be first used to capture the losses between virtual points at the transmitter and the receiver, and the resultant model can then be mapped to other AEs, which reduces the computational complexity. As for statistical modeling, it is either matrix-based or reference-antenna-based. In a matrix-based model, each independent sub-channel is represented by a complex Gaussian variable. On the other hand, reference-antenna-based models assume single-input single-output statistical propagation, for two reference antennas at the transmitter and the receiver, with array steering vectors. Finally, hybrid channel modeling combines the advantages of both deterministic and statistical approaches, where dominant paths can be individually captured by the deterministic method, while other paths can be statistically generated. This captures the spatial-temporal properties while allowing smooth time evolution and avoiding channel discontinuity.

For all these approaches, inter-stream channel correlation remains a significant challenge that needs to be addressed. While the Kronecker model is typically used to account for the correlation between sub-channels, this model leads to inconsistent measurements when the size of antenna arrays is large. This is because it assumes correlation to be separable, with a resultant matrix that is a product of two correlation matrices at the transmitter and the receiver. Virtual channel representations can be developed instead, by accounting for the mutual correlation between the transmitter and the receiver.

B. THz Channel Conditions

At THz frequencies, the channel response is dominated by molecular absorption losses. The LoS path loss due to water vapor molecules is illustrated in Fig. 2 (as a heatmap), between 0.1 THz and 10 THz, over a distance range of 30 m. It can be noted that the plot is dominated by spikes (in yellow) that originate due to excited molecule vibrations at specific resonant frequencies within the THz band. With certain spikes only appearing at specific distances (as reflected by the blue shade in the bottom-left corner), the available spectrum is divided into smaller distance-dependent windows. This means that increasing the communication range does not only increase the path loss, but also reduces the available transmission bandwidths. Furthermore, the total available bandwidth reduces as frequency increases (higher occurrence of absorption spikes and higher propagation losses). The absorption coefficient for a volumetric density depends on system temperature, system pressure, and absorption cross section [10]. All parameters that are required for absorption loss computations can be obtained from the high-resolution transmission molecular absorption database (HITRAN), some of which summarized in Table I.

Table I: Simulation Parameters and their Typical Values

| Parameter | Value |
|-----------|-------|
| $T$       | 396 K |
| $p$       | 0.1 atm |
| $q_i^{h,g}$ | 0.05 % |
| $f_i^{r,g}$ | (0 ~ 276.45) Hz |
| $\gamma$  | (~0.16 ~ 0.83) |
| $\delta_i^{h,g}$ | (~0.0409 ~ 0.0251) Hz |
| $S_i^{h,g}$ | (9.98 ~ 36 ~ 2.66 ~ 18) Hz m^2/molecule |
| $\alpha_{air}^{h,g}$ | (0.0023 ~ 0.1117) Hz |
| $\alpha_i^{h,g}$ | (0.052 ~ 0.916) Hz |

Note that molecular absorptions are followed by coherent reradiations that can be lumped in a high-power absorption noise factor. The resultant noise is thus dominated by the channel induced component (graphene-based electronic devices are low-noise), and it is colored over frequency.
Building on these THz channel characteristics, a three-dimensional end-to-end RT-based channel model for THz UMMIMO AoSA architectures is proposed in [8] for graphene-based nano-antenna arrays, where the corresponding path gains, array factors, and achievable capacities are studied. Due to large reflection losses, the THz channel is dominated by LoS and NLoS paths, while scattered and refracted rays can be neglected. Furthermore, the channel tends to be sparse with beamforming and ill-conditioned with SMX. Nevertheless, achieving good multiplexing gains in high-frequency point-to-point LoS environments is feasible when antenna spacings are much larger than the operating wavelength. The largest number of spatial degrees of freedom in a LoS environment at high frequencies is achieved via sparse antenna arrays, that generate spatially uncorrelated channel matrices, resulting in sparse multipath environments. The channel condition number, which is the ratio of the largest to smallest singular value of a channel matrix, is plotted in Fig. 3 as a function of the communication range (D) and the distance between AEs (Δ). Smaller condition numbers indicate better conditioned channels. Two regions of operation can be noted: region 1 with relatively large Δ values (upper-left side of Fig. 3), and region 2 with relatively small Δ values (where yellow curves indicate ill-conditioned channels). The dark-blue curves, in between yellow curves, represent orthogonality of channel paths or equality of singular values, that guarantee optimal AoSA designs. Building on these observations on channel characteristics, we next highlight several signal processing open research directions for THz UMMIMO.

IV. SIGNAL PROCESSING RESEARCH ADVANCES

Due to fundamental differences in signal and channel characteristics, classical signal processing problems have to be readdressed at the THz band. Such problems include, but are not limited to, accurate beamforming and beamsteering criteria, optimal precoding and combining methods, low-cost channel estimation paradigms, and near-optimal data detection. Compressed sensing techniques can be employed to solve most of these problems by taking advantage of the inherent sparsity at THz. We hereby highlight some relevant research advances.

A. Modulation

The limitations of nano-scale transceivers bound the ability to generate continuous carrier-based modulations. In fact, only very short pulses can be generated in the higher THz range with graphene at room temperature, with a corresponding power in the order of few milli-watts, which is not sufficient for long-distance communications. Pulse-based asymmetric on-off keying modulation spread in time (TS-OOK) is thus proposed in [11], and consists of trading very short pulses (one hundred femtosecond-long) among nano-devices as a logic one. It supports a very large number of nano-devices, that can transmit at very high rates, ranging from few Gb/sec to few Tb/sec. Most of the algorithms that are tailored for regular MIMO systems should be modified to account for pulse-based modulations, at least for the time being. But judging by the pace of growth in THz technologies, it is expected that regular carrier-based modulations will be the norm in the not-so-far future. Note that cognitive systems at THz can then adapt modulation types depending on system and channel conditions. An interesting signal processing exercise in this context would be to blindly estimate such modulations at the receiver side. The latter would be an extension to the well-investigated classical modulation classification problem.

B. Waveform Design and Beamforming

In order to make the best use of spectral windows, THz-specific optimized multi-carrier waveform designs are required, other than orthogonal frequency-division multiplexing (OFDM). Since the channel is assumed flat at THz, such designs would typically be single-carrier, with the possibility of encorporating carrier aggregation schemes. Furthermore, maintaining an efficient use of resources can be achieved through optimization frameworks that jointly control transmission power, sub-window allocation, and modulation formats. For example, a multi-wideband waveform design for distance-adaptive THz communications is developed in [13] to enable communications over long-distance networks. The optimization framework is designed to solve for the number of frames and transmission power, with the objective of maximizing the communication range. The optimization framework in [13] takes into consideration the characteristics of distance-varying spectral windows, as well as temporal broadening effects and delay spreads. This scheme severely exploits the transmit power, achieving 30 Gb/sec at 22.5 m communication range.

Similarly, efficient beamforming schemes are required, so as to overcome the high path loss and account for the distance-dependent and frequency-dependent characteristics of the THz channel. A hybrid beamforming scheme is developed in [15], with multi-carrier transmission, using analog beamforming for user grouping and digital beamforming with dynamic SAs at the baseband. An adaptive power allocation scheme is proposed for targeting different distances, alongside a SA selection algorithm that reduces the cost of radio frequency circuits. In the analog domain, different user groups can share the same frequency without correlation, and same user groups are allocated at orthogonal frequencies. In the digital domain, the data streams of a user group are assigned to specific SAs.
C. Multi-Carrier Antenna Configurations

In a plasmonic AoSA architecture, nano-antenna spacings can be significantly reduced, to the order of $\lambda_{\text{SPP}}$, while still avoiding mutual coupling effects. Placing AEs very close to each other, however, limits the beamforming gain by reducing the corresponding spatial sampling capabilities. In fact, the maximum distance separation $\delta$ between two AEs should be in the order of half operating wavelength $\lambda/2$ to avoid grating-lobe effects in beamforming. Towards that end, an interleaved antenna map is suggested in [14], in which neighboring AEs operate at different absorption transmission windows.

Similarly, much larger same-frequency SA separations $\Delta$ are required to achieve good multiplexing gains. Therefore, a sparse interleaving antenna map is required. The key enabler for such frequency-interleaved maps is the ability to dynamically tune each AE to a specific resonant frequency, without modifying its physical dimensions. This can be achieved at high frequencies by simple material doping or electrostatic bias. For frequencies below $1$ THz, software-defined plasmonic metamaterials also exist. Figure 4 illustrates the interleaving schemes, at the level of SAs or AEs (bottom-right corner), where same colors represent same frequencies. The separation between two AEs tuned to the same frequency is $\delta = \lambda/2$, and that between two AEs tuned to different frequencies is $\delta = \lambda_{\text{SPP}}$. Note that each AE is individually powered, which results in larger antenna array gains. In fact, reconfigurability, adaptability and scalability are key target features for all types of future THz tranceivers, not just the plasmonic-based ones.

D. Spatial Modulation

Spatial modulation (SM) can be thought of as a spectrum and power-efficient paradigm for THz UM-MIMO. Instead of antenna frequency maps, as those shown in Fig. 4, for mult(carrier designs, we can design antenna maps that turn AEs on and off in the context of a SM setup. Due to inherent large array dimensions, a significant number of information bits can be assigned to antenna locations in these maps. Up to our knowledge, SM at THz has never been addressed in the literature. In fact, SM at very high frequencies is challenging because of LoS-dominance. Based on the previous analysis of THz channel conditions in Sec. III it can be noted that frequency, communication range, and separations between AEs can be tuned for favorable propagation settings.

Adaptive and hierarchical SM solutions can be achieved by mapping information bits to antenna locations, at the level of SAs or AEs. We perceive the antenna arrays as large fully-configurable graphene sheets of AEs that can get partially activated. Such arrays can be adapted in real time by activating a specific set of AEs, to achieve a target bit rate at a specific communication range (as per our arguments in previous sections). Sample bit error rate (BER) results for several SM and SMX schemes are shown in Fig. 5. Note that Region 2 optimized corresponds to operations in region 2 of Fig. 3 with corresponding compact designs, but with dimension tuning to guarantee favorable propagation conditions (sufficient channel diversity). We observe that operations in region 2 can be made efficient, and that SMX is more sensitive to channel conditions than SM. Note that SM can be combined with frequency-interleaved antenna map designs, so as to come up with generic index modulation solutions. Such solutions can take full advantage of available resources by assigning information bits to frequency allocations as well.

V. Prospective Research Directions

Having detailed the channel conditions and research trends, we hereby discuss a select few prospect THz UM-MIMO use cases that are more likely to get realized in the near future. Candidate use cases should provide good LoS conditions and should support sufficient design adaptability and flexibility. In what follows, we promote the use of THz communications at the intersection of communications and sensing, as an alternative to wired backbone connectivity in data centers, as part of large intelligent surface deployments, as well as in the context of mobile wireless mid-range communications.
A. Communications and Sensing

Many applications can be piggybacked onto THz wireless communications, particularly in the areas of imaging, localization, and sensing. Perhaps the most interesting of these applications that could make use of UM-MIMO is gas sensing. The specific absorption spectral characteristics of molecules serve as fingerprints for specific gaseous compositions. Hence, by shooting THz signals into a medium, and then estimating the channel response at the receiver side, using time-domain spectroscopy, for example, the molecular composition of this medium can be detected. UM-MIMO systems can enable sensing over extended distances, where the distance-dependent behavior of molecular absorptions can be mitigated to correct measurements. This could be exploited to monitor air pollution from a distance. Furthermore, THz signals are used to monitor other physical parameters, such as temperature and displacement. They are also used for medical diagnostic purposes. UM-MIMO nano-antenna array configurations can enhance the accuracy or such sensors by exploiting the spatial degrees of freedom to increase sensing resolution.

Furthermore, the field of nano-technology continues to expand with the advent of novel nano-materials. For instance, graphene has been recently used to develop efficient nanobatteries, nano-processors, and nano-sensors. EM communications among nano-devices, however, suffer from several limitations, which are mainly due to the small sizes and low energy levels. Towards this end, low-power and low-cost UM-MIMO nano-antenna arrays can be used to communicate sensing information over a distributed wireless sensing network.

B. Data Centers

Due to the large number of networked computers and storage devices in data centers, novel communication technologies are required to facilitate accessing and processing of data. In data centers, servers are typically arranged in multiple racks, and wired connections are often sought for convenience. Wiring a massive number of servers, however, increases the size of data centers and reduces system efficiency. To the contrary, wireless links can reduce system costs and yield more energy efficient data centers by eliminating the need for power-hungry switches. Such links should be complemented by efficient networking solutions and scheduling mechanisms, that allocate channels to servers based on the traffic demand.

The high data rates make THz communications a strong candidate for wireless data centers. Furthermore, the reconfigurability of THz antenna arrays can be leveraged to support multiple inter-rack and intra-rack communication links. THz UM-MIMO transceivers with high power, low noise figures, and good sensitivity can thus be optimized in such static environments. Note that THz for data centers is already attracting attention. For example, TERAPOD (Horizon 2020 project supported by the European Union) is using data centers as a proof-of-concept deployment of end-to-end THz wireless links. In particular, recently-proposed naturally-cooled underwater data centers can make the best use of the THz band. These enclosed data centers can control the gaseous composition (using nitrogen) to reduce absorption losses.

C. Large Intelligent Surfaces

Making the entire environment intelligent and active for communication purposes is one of the visions for beyond fifth generation (5G) communication paradigms. Future man-made structures, such as buildings, roads, and walls, are thus expected to be electronically active. In this context, the concept of large intelligent surfaces (LISs) has been recently proposed, in which surfaces scale up beyond conventional antenna arrays, and act as transmitting and receiving structures in an environment. These surfaces should achieve extremely high data rates, support efficient wireless charging capabilities, and enable high-precision sensing applications. LISs can be particularly realized via THz UM-MIMO because of two main favorable conditions. First, they are more likely to yield perfect LoS indoor and outdoor propagation environments. Second, they impose little restrictions on how AEs can be spread. Hence, mutual coupling effects and antenna correlations can easily be avoided, and the favorable propagation settings of region 1 in Fig. 5 can easily be met. LISs further support simple channel estimation techniques and simple feedback mechanisms, which are important for low-latency applications.

D. Mid-Range Mobile Communications

Mid-range wireless mobile communication applications, that require several meters of distance coverage, are the holy grail of THz communications, and are the main motive behind developing UM-MIMO techniques that operate efficiently at the THz band. THz communications promise to support ultra-broadband and ultra-high-speed applications, such as terabit wireless personal/local area networks. Recently, the IEEE 802.15 wireless personal network group formed a THz interest group, and several experiments on THz wave propagation in room environments have been conducted. It is demonstrated that transmission windows up to 500 GHz can support personal wireless networks with 20 Gb/sec peak rates. Adaptive and compact THz UM-MIMO array designs allow for sharing transceiver resources, tuning carrier frequencies, and directing antenna beams to multiple users.

THz communications bring many exciting opportunities for vehicular networks as well. In fact, transmitting at high data rates causes the system to be quasi-static, even when users are mobile. Furthermore, moving to high carrier frequencies minimizes the Doppler effect. Similarly, fast-moving unmanned aerial vehicles or drones are highly dependent on the throughout, reliability, and latency of wireless systems, which makes THz UM-MIMO a candidate solution.

One of the main challenges in these mobile setups is to mitigate the effect of blockage. Blockage can easily occur over the medium due to the small wavelengths. It can also easily occur at the source due to tiny suspended particles that are big enough to block AEs. Nevertheless, while it is not easy to overcome all the challenges that govern THz wireless communications, a plausible solution, and an important research direction, is to allow for the co-existence of THz, mmWave, and microwave systems. In the mean time, high mobility can still be treated by the more mature mmWave solutions, while backhaul transmissions can be conducted at the THz band.
VI. CONCLUSION

In this paper, we examined the characteristics of the THz channel to advocate the potential of UM-MIMO systems at high frequencies. With proper configurations, UM-MIMO antenna arrays can overcome the distance and power limitations. We argued that graphene-based nano-antenna arrays, in particular, can efficiently realize THz UM-MIMO systems. We defined multiple research advances, from a signal processing perspective, that are critical for increasing the efficiency of THz communications, including signal modulation, waveform design, and resource allocation. Finally, building on all preceding arguments, we envisioned select few use-cases that are likely to realize THz UM-MIMO in the near future.

BIographies

Alice Faisal (S’18) is a senior electrical and computer engineering student at Effat University, Jeddah, Saudi Arabia. She is currently the chair of IEEE women in engineering affinity group at Effat University student branch. Her research interests are in the areas of wireless communications and signal processing.

Hadi Sarieddeen (S’13–M’18) received the B.E. degree (summa cum laude) in computer and communications engineering from Notre Dame University–La Louviere (NDU), Zouk Mosbeh, Lebanon, in 2013, and the Ph.D. degree in electrical and computer engineering from the American University of Beirut (AUB), Beirut, Lebanon, in 2018. He is currently a postdoctoral research fellow in the Electrical and Mathematical Sciences and Engineering (CEMSE) Division at King Abdullah University of Science and Technology (KAUST), Thuwal, Makkah Province, Saudi Arabia. His research interests are in the areas of communication theory and signal processing for wireless communications, with emphasis on large, massive, and ultra-massive MIMO systems and terahertz communications. He was a recipient of the General Khalil Kanaan Award at NDU in 2013 for ranking first on the graduating class, and the National Council for Scientific Research Doctoral Scholarship Award at AUB in 2016.

Hayssam Dahrouj (S’02, M’11, SM’15) received his B.E. degree (with high distinction) in computer and communications engineering from the American University of Beirut (AUB), Beirut, in 2005, and his Ph.D. degree in electrical and computer engineering from the University of Toronto (UoT), Canada, in 2010. In May 2015, he joined the Department of Electrical and Computer Engineering at Effat University as an assistant professor, and also became a visiting scholar at KAUST. Between April 2014 and May 2015, he was with the Computer, Electrical and Mathematical Sciences and Engineering group at KAUST as a research associate. Prior to joining KAUST, he was an industrial postdoctoral fellow at UoT, in collaboration with BLINQ Networks Inc., Kanata, Canada. His main research interests include multi-base signal processing in cloud-radio access networks, multi-sensor networks, free-space optics, machine learning, convex optimization, and distributed algorithms.

Tareq Y. Al-Naffouri (M’10–SM’18) Tareq Al-Naffouri received the B.S. degrees in mathematics and electrical engineering (with first honors) from King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, the M.S. degree in electrical engineering from the Georgia Institute of Technology, Atlanta, in 1998, and the Ph.D. degree in electrical engineering from Stanford University, Stanford, CA, in 2004. He was a visiting scholar at Caltech, Pasadena, CA in 2005 and summer 2006. He was a Fulbright scholar at USC in 2008. He has held internships at NEC Research Labs, Tokyo, Japan, in 1998, Adaptive Systems Lab, UCLA in 1999, National Semiconductor, Santa Clara, CA, in 2001 and 2002, and Becceem Communications Santa Clara, CA, in 2004. He is currently an Associate Professor at the Electrical Engineering Department, KAUST. His research interests lie in the areas of sparse, adaptive, and statistical signal processing and their applications, localization, machine learning, and network information theory.

Mohamed-Slim Alouini (S’94–M’98–SM’03–F’09) was born in Tunis, Tunisia. He received the Ph.D. degree in Electrical Engineering from the California Institute of Technology (Caltech), Pasadena, CA, USA, in 1998. He served as a faculty member in the University of Minnesota, Minneapolis, MN, USA, then in the Texas A&M University at Qatar, Education City, Doha, Qatar before joining King Abdullah University of Science and Technology (KAUST), Thuwal, Makkah Province, Saudi Arabia as a Professor of Electrical Engineering in 2009. His current research interests include the modeling, design, and performance analysis of wireless communication systems.

REFERENCES

[1] I. F. Akyildiz, J. M. Jornet, and C. Han, “TeraNets: ultra-broadband communication networks in the terahertz band,” IEEE Wireless Commun., vol. 21, no. 4, pp. 130–135, Aug. 2014.

[2] S. Rangan, T. S. Rappaport, and E. Erkip, “Millimeter-wave cellular wireless networks: Potentials and challenges,” Proceedings of the IEEE, vol. 102, no. 3, pp. 366–385, Mar. 2014.

[3] L. Ju, B. Geng, J. Hong, C. Girit, M. Martin, Z. Hao, H. A. Bechtel, X. Liang, A. Zettl, Y. R. Shen et al., “Graphene plasmonics for tunable terahertz metamaterials,” Nature nanotechnology, vol. 6, no. 10, p. 630, 2011.

[4] H. Hafez, S. Kovalev, J. Deinert, Z. Mics, B. Green, N. Awari, M. Chen, S. Germanskiyi, U. Lehnerz, J. Teichert et al., “Extremely efficient terahertz high-harmonic generation in graphene by hot Dirac fermions.” Nature, 2018.

[5] I. F. Akyildiz and J. M. Jornet, “Realizing ultra-massive MIMO (1024×1024) communication in the (0.06–10) terahertz band,” Nano Communication Networks, vol. 8, pp. 46–54, 2016.

[6] E. Torkildson, U. Madhow, and M. Rodwell, “Indoor millimeter wave MIMO: Feasibility and performance,” IEEE Trans. Wireless Commun., vol. 10, no. 12, pp. 4150–4160, Dec. 2011.

[7] C. Lin and G. Y. L. Li, “Terahertz communications: An array-of-subarrays solution,” IEEE Communications Magazine, vol. 54, no. 12, pp. 124–131, December 2016.

[8] C. Han and J. M. Jornet, and I. F. Akyildiz, “Ultra-massive MIMO channel modeling for graphene-enabled terahertz-band communications,” in Proc. IEEE Vehic. Technol. Conf. (VTC), Jun. 2018, pp. 1–5.

[9] C. Han and Y. Chen, “Propagation modeling for wireless communications in the terahertz band,” IEEE Commun. Mag., vol. 56, no. 6, pp. 96–9, Jun. 2018.

[10] J. M. Jornet and I. F. Akyildiz, “Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band,” IEEE Trans. Wireless Commun., vol. 10, no. 10, pp. 3211–3221, Oct. 2011.

[11] ———, “Femtosecond-long pulse-based modulation for terahertz band communication in nanonetworks,” IEEE Trans. Commun., vol. 62, no. 5, pp. 1742–1754, May 2014.

[12] C. Han and I. F. Akyildiz, “Distance-aware bandwidth-adaptive resource allocation for wireless systems in the terahertz band,” IEEE Trans. THz Sci. Technol., vol. 6, no. 4, pp. 541–553, Jul. 2016.

[13] C. Han, A. O. Bicen, and I. F. Akyildiz, “Multi-wideband waveform design for distance-adaptive wireless communications in the terahertz band,” IEEE Trans. Signal Process., vol. 64, no. 4, pp. 910–922, Feb. 2016.

[14] L. M. Zakrajsek, D. A. Pados, and J. M. Jornet, “Design and performance analysis of ultra-massive multi-carrier multiple input multiple output communications in the terahertz band,” in Proc. SPIE, vol. 10209, Apr. 2017, pp. P1–P12.

[15] C. Lin and G. Y. Li, “Adaptive beamforming with resource allocation for distance-aware multi-user indoor terahertz communications,” IEEE Trans. Commun., vol. 63, no. 8, pp. 2985–2995, Aug. 2015.