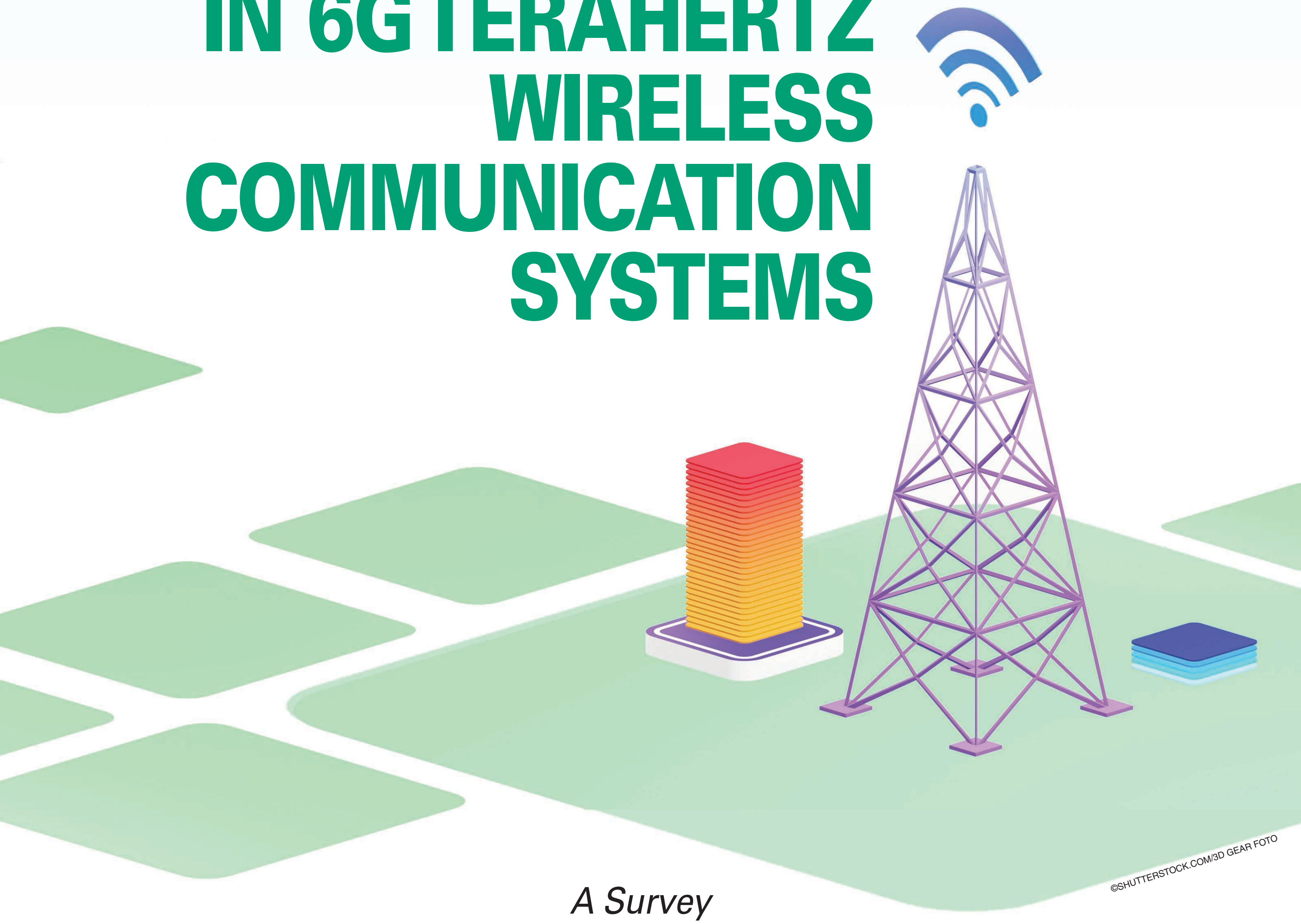
KEY TECHNOLOGIES IN 6G TERAHERTZ WIRELESS COMMUNICATION SYSTEMS



A Survey

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Terahertz (THz) technologies have great potential in future 6G wireless communication systems. In this article, we comprehensively survey key technologies in 6G THz wireless communication systems, focusing on THz channel modeling, multibeam antenna design, front-end chip design, baseband signal processing, and resource management.

THz channel characterization and modeling are the fundamental basis for the design, parameter optimization, and test of THz communication systems. THz multibeam antennas and front-end chips are the important components at the front end, while THz baseband signal processing and resource management play key roles in determining the performance of THz communication systems. The advances in and future research challenges of these key technologies for THz wireless communication systems are discussed.

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IT IS FORESEEABLE THAT 5G WILL SOON REACH ITS PERFORMANCE BOTTLENECK, FACING THE CONTRADICTION BETWEEN LIMITED SPECTRUM RESOURCES AND A RAPID INCREASE IN DEMAND FOR HIGH-DATA-RATE SERVICES.

Overview

The performance of 5G wireless communication systems has been greatly improved due to the application of high-frequency technologies, i.e., millimeter-wave (mm-wave) communications. Sufficient bandwidths can be provided in 5G to meet current applications, such as ultra-high-definition video transmission and virtual reality. However, it is foreseeable that 5G will soon reach its performance bottleneck, facing the contradiction between limited spectrum resources and a rapid increase in demand for high data rate services. There will be plenty of new applications that require greater bandwidth in future 6G wireless communication systems. With spectra ranging from 0.1 to 10 THz, THz communications are considered to be one of the key technologies for 6G [1].

Compared with the mm-wave band, the THz band can provide higher continuous bandwidth and a greater transmission rate. In addition, the size of the transceiver tends to be much smaller due to the shorter wavelength of THz bands, which makes it easier to integrate with the ultramassive antenna array. Another band that can provide huge bandwidth resources is the optical wireless communication band. Compared with this, the THz band is less susceptible to environmental impacts, such as clouds, rain, and fog. For indoor communications, incoherent receivers (Rxs) in the optical frequency band have poor sensitivity, high diffuse reflection loss, and human safety restrictions, resulting in limited transmission power and data rates. Therefore, THz is a more suitable alternative for indoor communications.

Although THz communication is attractive and has great potential, some commonly used technologies in traditional communication systems are limited and hard to implement in the THz band. For real applications of THz communications, there are several key technologies that need to be studied, including channel modeling, multibeam antenna, front-end chip design, baseband signal processing, and resource management for both the transmitter (Tx) and Rx. The relationships of these five key technologies are shown in Figure 1.

An accurate THz channel model is the prerequisite of baseband signal processing and resource management.

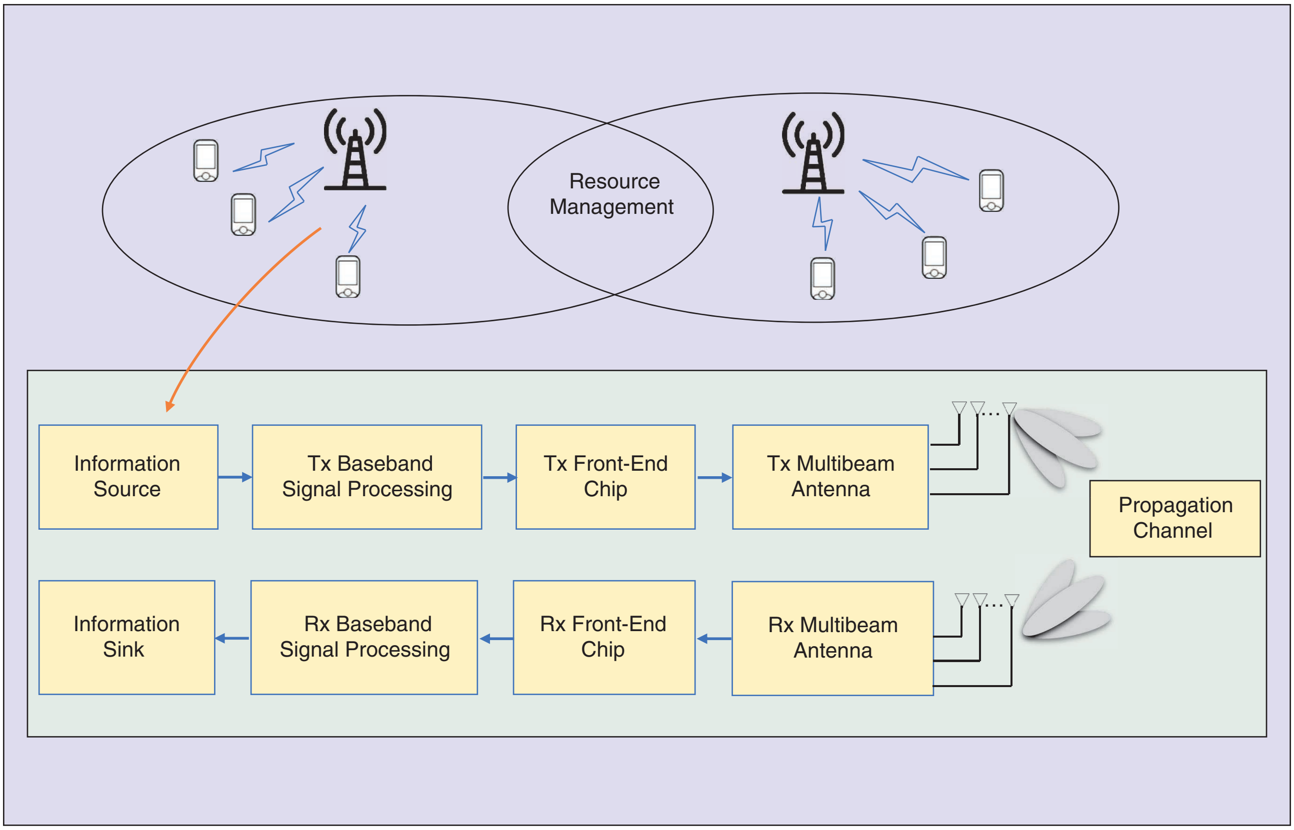

FIGURE 1 The relationships among key technologies in THz communication systems.

The influence of the antenna should be considered in the study of THz channel modeling. Different configurations of antenna arrays will cause different channel characteristics that cannot be ignored. The front-end chip design provides hardware support for other key technologies. In addition to these five key technologies, there are still many bottlenecks that need to be overcome, such as the THz signal source and the integration of THz modules. However, in this article, we focus on these five key THz technologies due to limited space.

THz Channel Characterization and Modeling

Wireless communication is realized through the propagation of electromagnetic (EM) waves in space. The propagation channel has a significant influence on the performance of wireless communication systems. Link- and system-level simulation evaluations of communication systems also need a channel model that can accurately describe the channel characteristics [2]. The study of the THz channel model is the basis for the design and optimization of THz communication systems. The channel characteristics of the THz band are quite different from those of the traditional lower-frequency bands, so the traditional channel model is no longer applicable to the THz band. There is an urgent need for in-depth research on the THz channel models that can accurately reflect the characteristics of THz propagation.

THz Channel Characteristics

It is necessary to analyze the new statistical characteristics of the corresponding channel for the application of any advanced communication technologies and emergence of new frequency bands. The study of the THz channel model should be based on an in-depth knowledge of the characteristics of these channels.

THz Atmosphere Absorption

The attenuation of the atmosphere on the communication link in the THz band is affected by different weather conditions, such as fog, rain, snow, and humidity. On a foggy day, the THz absorption coefficient around 240 GHz is about 8 dB/km, which is much smaller than the 200-THz infrared wave absorption coefficient (200 dB/km). It should be noted that, from 200 GHz to 10 THz, the attenuation of water vapor in the atmosphere is dominant.

When the THz wave passes through the atmosphere of several kilometers, the change of the refractive index of the atmosphere may change the plane phase front of the beam. The rising warm current and atmospheric turbulence near the ground will produce local temperature, air pressure, or humidity gradients that will cause small changes in the refractive index near the beam wavefront.

ALTHOUGH THZ COMMUNICATION IS ATTRACTIVE AND HAS GREAT POTENTIAL, SOME COMMONLY USED TECHNOLOGIES IN TRADITIONAL COMMUNICATION SYSTEMS ARE LIMITED AND HARD TO IMPLEMENT IN THE THZ BAND.

Therefore, at the receiving end, the cross section of the beam appears as a speckle pattern.

THz Propagation Mechanisms

The propagation of EM waves is divided into direct radiation, reflection, scattering, and diffraction. The 300-GHz wave has a wavelength of 1 mm, which is close to the roughness of the surface of common objects, such as wallpaper and a cement floor. For higher frequencies, the wavelength is even smaller than the undulation of the reflective surface. When EM waves are incident on such a plane, they produce not only specular reflection components but also a lot of diffuse components, which was studied in [3]. When it is close to the optical band, almost all reflections are diffuse unless the reflection plane is mirror-like.

Regardless of specular or diffuse reflection, each reflection will bring great loss. Therefore, in the THz band, it is difficult for the multiple reflection paths to reach the minimum detectable power of the Rxs. As a result, the number of paths is greatly reduced compared with the lower-frequency band. In addition, because the THz wavelength is small, there is less diffraction when propagating in space, so the THz wave has good propagation direction, and the line-of-sight path transmission is usually adopted in communication.

THz Channel Models

Channel models are categorized as deterministic and stochastic. The basic idea of deterministic channel modeling is to analyze the transmission characteristics of the channel in a determined target environment based on the EM-field propagation theory. The model parameters of stochastic channel modeling include random variables, and mathematical statistical properties are used to describe the transmission of wireless channels.

THz Deterministic Channel Models

Deterministic channel modeling approaches include the finite difference time domain method, ray tracing technique, and so on. THz band ray tracing is often used to simulate signal propagation in an indoor environment. Deterministic channel modeling methods, such as ray tracing, need to have a clear description of the surroundings, so they are suitable for analyzing a deterministic environment. Ray tracing is widely used to predict the propagation characteristics and calculate the amplitude,

ANTENNAS ARE THE KEY COMPONENTS LOCATED AT THE FRONT END OF THZ WIRELESS SYSTEMS, AND THEIR ELECTRICAL PROPERTIES CAN DIRECTLY AFFECT THE OVERALL SYSTEM PERFORMANCE.

phase, delay, and polarization of each ray according to the radio wave propagation theory. However, the amount of computation for deterministic simulation is very large and time-consuming. This problem has been alleviated with the continuous development of computer technology and improvement of computing power.

THz Stochastic Channel Models

Stochastic channel models include the geometry- (GBSM) and correlation-based stochastic channel model (CBSM). A GBSM is generated according to the geometric relationship between the actual scatterers and the Tx/Rx, while a CBSM is generated based on the correlation properties of the channels. Most standard channel models use GBSMs, such as the 3rd Generation Partnership Project Technical Report 38.901, and they are more widely employed in performance simulations of modern communication systems. In the THz band, GBSMs are more suitable for system design, network optimization, and performance evaluation compared with deterministic channel models because of lower complexity.

All of the THz channel characteristics need to be considered to model the THz channel accurately. The channel characteristics include not only the propagation properties but also new features in applications. For example, due to the large path loss in the THz band, ultramassive antenna arrays are usually used at both sides of the transceivers to compensate for the huge loss. Therefore, the spatial nonstationary characteristics caused by the large-scale antenna array need to be considered.

The large bandwidth of THz communication results in frequency nonstationarity. In addition, environmental changes or slow movement of the transceiver bring time domain nonstationarity. In [4], a novel space–time–frequency nonstationary GBSM considering the scattering characteristics of the THz band was proposed. It can be applied to different THz communication scenarios by adjusting the parameters. The cumulative distribution functions (CDFs) of angle deviations in a cluster are compared between the stochastic channel model and measurement data, as shown in Figure 2.

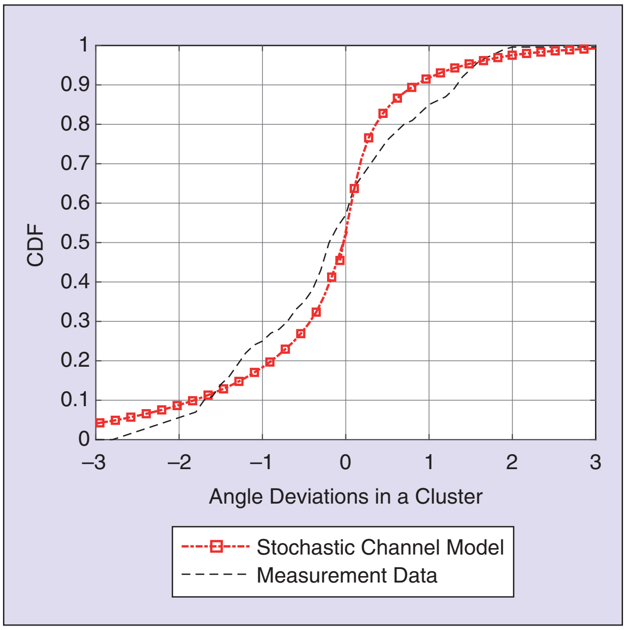

FIGURE 2 A comparison of the CDFs of angle deviations in a cluster between a stochastic channel model and measurement data. (Source: [4].)

THz Multibeam Antennas

Antennas are the key components located at the front end of THz wireless systems, and their electrical properties can directly affect the overall system performance. At THz bands, the propagation loss is much higher than that at the microwave and mm-wave frequencies. In addition, the output power is also very limited in currently available solid-state THz sources and amplifiers, thereby limiting the equivalent isotropic radiated power at a small level. Therefore, to maintain the required signal-to-noise ratio (SNR) for the wireless links, THz antennas have become of great importance. They can be classified into four categories according to their principles of operation, including the photoconductive, metallic, dielectric, and novel material antennas.

The THz photoconductive antenna is based on the direct radiation of THz signals generated by photoconductive materials when they are illuminated by a laser pulse. A THz photoconductive antenna consists of a photoconductive substrate, an antenna gap, and two antenna electrodes at both sides of the gap. Its performance is determined by the properties of the femtosecond laser pulse, photoconductive semiconductor substrate, and geometry of the antenna electrodes. In particular, the shape of the electrodes can be designed to control the operational bandwidth, polarization, and pattern of the THz radiation.

The THz metallic antennas mainly rely on the development of micromachining technologies, including laser milling and molding replication, additive manufacturing, and lithography. Several types of THz metallic antennas have been investigated, including horn antennas, metallic plate lenses, waveguide-fed slot arrays, and reflectarrays. These antennas usually can generate directive beams with a high gain [5]. Particularly, for planar THz metallic antennas, low-loss metallic waveguides, such as the gap and hollow waveguides, are more amenable for the THz bands. With respect to the manufacturing of these THz metallic antennas, the surface roughness and dimension precision are critical for achieving a higher radiation efficiency.

The third kind is the THz dielectric antenna, which utilizes dielectric materials and eliminates ohmic loss. Various types of lenses have been explored by shaping the dielectric material into a certain convex geometry, which borrows the lens idea from the optics community. In addition to the spherical homogeneous dielectric lenses, quasi-planar dielectric lens antennas have also been studied using additive manufacturing technology [6]. These lenses are often jointly used with photoconductive antenna elements or on-chip planar antennas that are inherently low gain.

Other than conventional materials, new substances have been actively explored to achieve THz radiation or introduce reconfigurability into THz antennas and arrays. For example, carbon nanotubes have been considered to achieve multiband radiation at THz frequencies. Graphene has also been studied for enabling beam steering of THz leaky wave antennas. Other phase change materials, including vanadium dioxide and liquid crystals, are also promising candidates for producing THz steerable beams.

AT THE THZ BAND, IT IS VERY CHALLENGING TO ASSEMBLE SEPARATE CHIPS WITH HIGH ACCURACY AND LOW PARASITIC EFFECT.

To achieve long-range communication and detection, THz antennas with a high gain (e.g., >30 dBi) are often required to combat the severe path loss. However, this poses difficulties in positioning accuracy due to the greatly reduced beamwidth. Therefore, as to what is being adopted in 5G and satellite communications, multibeam antennas are highly desirable because they can provide high-gain beams and support a certain angular coverage.

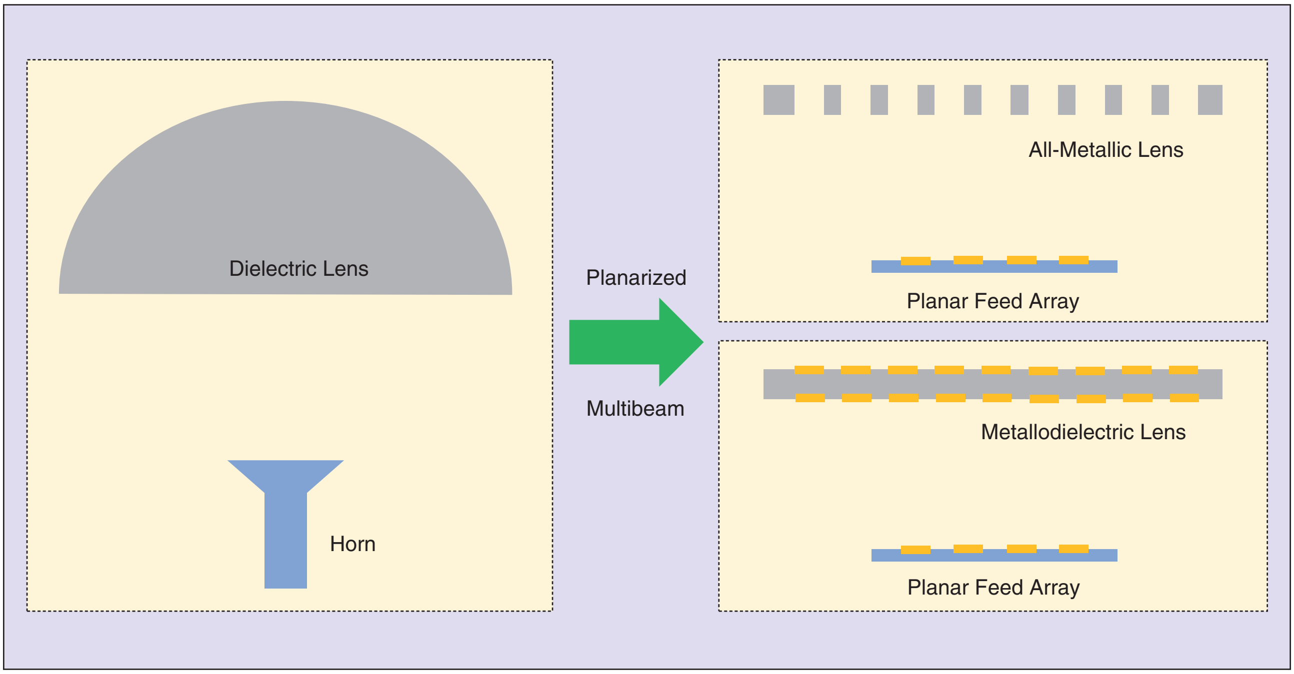

FIGURE 3 The configuration of THz multibeam antennas using planarized lenses and feed arrays.

***TABLE 1** A comparison of the properties of different types of THz antennas.*

Antenna Type	*Photoconductive Antenna*	*Metallic Antenna*	*Dielectric Antenna*	*New Material Antenna*
Gain	Low	High	High	Low
Efficiency	Moderate	Moderate	High	Low
Ease of integration	Good	Good	Poor	Moderate

OVER THE THZ BAND, AN ANTENNA ARRAY IS MORE COMPACT COMPARED WITH THAT IN A LOWER BAND SYSTEM.

In contrast to most previous research campaigns on single-beam THz antennas, which utilize a bulky dielectric lens and horn feed, a planarized configuration for multibeam radiation can be employed, as seen in Figure 3. It contains a flat lens, made of either all metallic structures or stacked metallodielectric multilayer structures, and a planar feed array implemented using low-gain elements fed by metallic waveguides or substrate-integrated waveguides (SIWs). It should be noted that all of the four kinds of THz antennas mentioned can be employed to form a feed array for achieving multibeam radiation functionality. A summary comparison of the different types of THz antennas is given in Table 1.

THz Front-End Chip Design

The THz front-end chip is a key technology for 6G wireless communication. Its architecture, functionality, performance, and cost directly determine those of whole systems.

Classical Design Method for the Radio-Frequency Front End

Conventionally, as shown in Figure 4, radio-frequency (RF) front ends are mainly divided into two categories, i.e., EM field and active circuit. The functional blocks are designed and measured separately and then assembled together. As shown in Figure 4(a), this classical design method is used to realize an active tag, which includes several commercial blocks. For some applications, as shown in Figure 4(b), it is

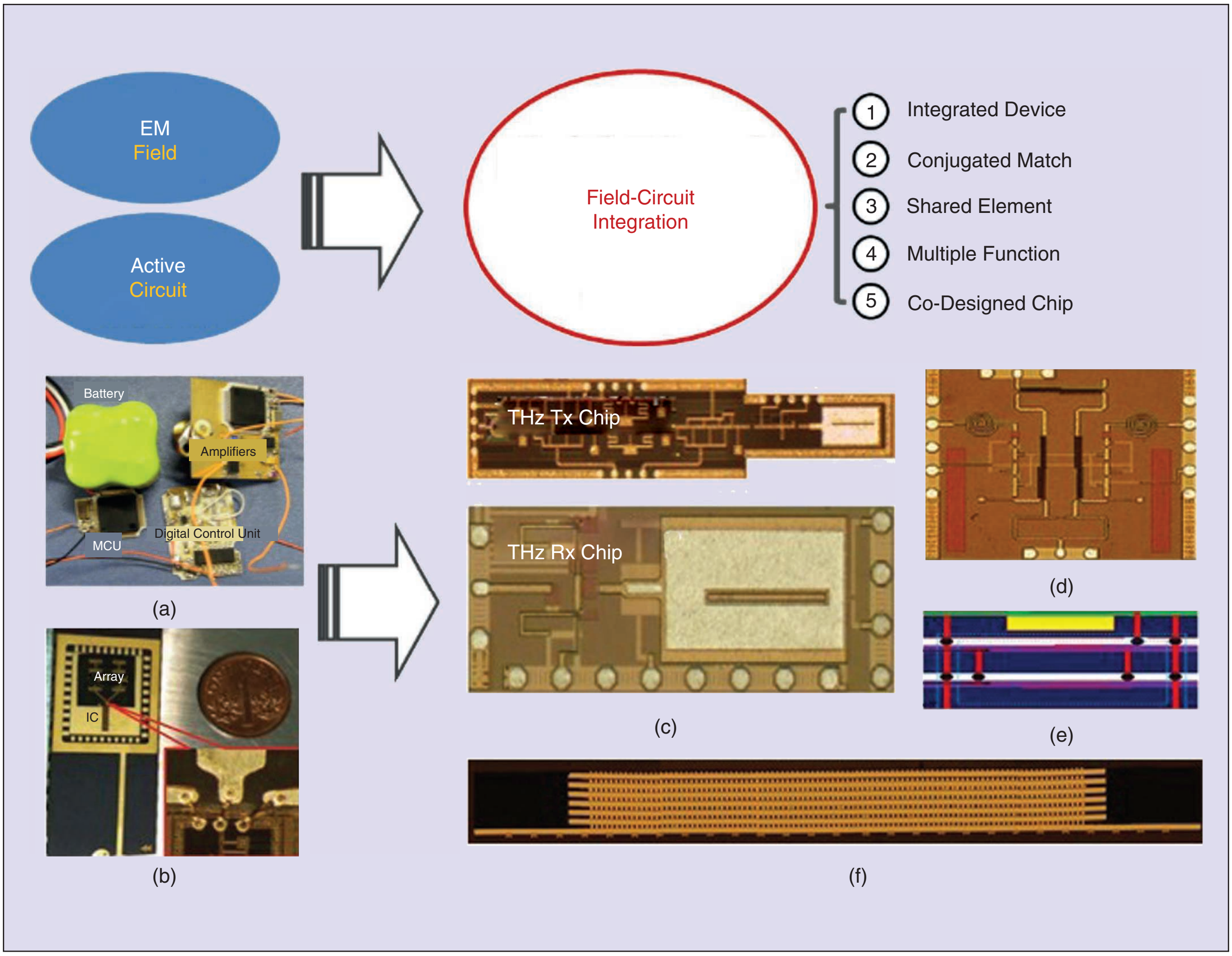

FIGURE 4 The paradigm shift for the design of THz front-end chips [7], [9]. (a) An active tag including several separate commercial blocks. (b) An mm-wave receiver using conventional bonding wire to connect circuit chip and antenna array. (c) A fully integrated THz, Tx, and Rx chips with antennas in a same silicon process. (d) A wideband mixer co-designed with passive and active circuits. (e) An antenna is cosimulated with circuit chip to reduce interference. (f) A co-designed chip for 3D integrated circuits. MCU: microcontroller unit; MOD: modulator; PA: power amplifier; VCO: voltage-controlled oscillator.

necessary to design the antenna or integrated circuit (IC) specifically and separately.

Paradigm Shift for the THz IC: Field-Circuit Integration

The described classical method is efficient for the RF and even mm-wave bands. However, at the THz band, it is very challenging to assemble separate blocks with high accuracy and low parasitic effect. First, the physical size of each THz block is very small. Second, the assemble/fabrication tolerance is not negligible to the THz wavelength. Third, the interconnection between THz blocks is lossy using conventional bonding wires.

Therefore, a paradigm shift is required for THz front-end chip design. As shown in Figure 4, one promising approach is field-circuit integration (FCI) by consolidating a multidisciplinary perspective of active circuits and the EM field. In particular, FCI may feature the following five characteristics:

- *Integrated devices*: Based on the FCI approach, it is straightforward to expect a fully integrated THz system-on-chip. As shown in Figure 4(c), using the same commercial process, a 0.4-THz Tx/Rx chipset inherently integrates several blocks [7].
- *Conjugated match*: In a conventional RF front end, all circuit blocks use the same 50 Ω for matching, which benefits the stand-alone design and measurement but also limits the design freedom. The antenna and tripler in Figure 4(c) and [7] are co-designed with a conjugated match at 0.4 THz.
- *Shared elements*: The FCI approach also opens the door to share element(s) with different blocks. As shown in Figure 4(c) and [7], the designed SIW operates as a slot antenna and also works as a high-pass filter to suppress unwanted fundamental and second harmonic signals by 50 and 30 dB, respectively. In [8], a simple patch is creatively shared for the power divider/combiner, matching, and also radiating at 146 GHz.
- *Multiple functions*: By integrating the EM field and active circuits, it is possible to achieve a wide bandwidth. As shown in Figure 4(d), the Wilkinson power divider and Lange coupler are inherently integrated with two single-ended mixers to cover 73–138 GHz. This wide bandwidth enables multiple functions for 77-GHz automotive radars, 94-GHz imaging, and 122/135-GHz high-speed communications.
- *Co-designed front-end chips*: FCI is rooted in co-design and is expected to significantly benefit THz front-end chips. As shown in Figure 4(e) and [9], an antenna is cosimulated with a circuit chip to reduce the EM interference up to 40 dB. As shown in Figure 4(f), co-design is explored for mechanical warpage and thermal isolation.

In summary, THz front-end chips are the cornerstones for many emerging applications, but they also face several challenges. The FCI method is a paradigm shift for THz front-end chip design and a promising approach to address these issues. Moreover, it is expected to prompt interdisciplinary research in the EM field, active circuits, and even multiphysics.

THE PECULIARITIES OF THE THZ SPECTRUM BRING SOME CHALLENGES AND OPPORTUNITIES FOR SOLVING THE RRM PROBLEM.

THz Baseband Signal Processing

At the current stage, there is no standardized baseband system model for THz wireless communications. Both single-carrier (SC) and multicarrier (MC) modulations are potential candidate schemes. The MC modulation can be in the form of orthogonal frequency-division multiplexing (OFDM) or carrier aggregation (CA) with multiple nonoverlapping SCs. CA is preferred when band splitting and spectrum shrinking due to molecular absorptions happen in a THz channel [10]. In addition to the carrier-based continuous-wave signals, pulse-based transmission has also been suggested.

THz Channel Estimation

Channel estimation is required for constructing the precoding and combining matrices on the transceiver side [10]. From the "THz Channel Characterization and Modeling" section, a channel in the THz band generally features higher sparsity and frequency nonstationarity compared with that in lower-frequency bands. In SC and pulse-based THz communications, sparse channel estimations based on compressive sensing (CS) algorithms have been proposed, including compressive sampling matching pursuit, approximate message passing (AMP), and so on. Numerical results showed the advantage of CS-based channel estimation over conventional least squares (LS) and linear minimum mean-square error (LMMSE) estimations.

Recently, machine learning-based channel estimation methods have also emerged. In [11], an estimation scheme of deep kernel learning based on the Gaussian process (GP) regression was proposed. The resulting channel estimator is a five-layer deep neural network followed by an additive GP layer. It is more efficient compared with classic linear estimation approaches. To account for the nonstationarity of THz beam-space channels, channel tracking algorithms have also been proposed. As for channel estimation in THz communications with OFDM modulation, a joint activity detection and channel estimation method called *multirank aware sparse algorithm* was proposed by exploiting the joint sparse and low-rank structure of THz channels [10].

In THz-based WLANs, the main objectives are to increase the coverage and achievable data rate.

THz Channel Coding

At the rate of the terabits-per-second level, low-latency and energy-efficient channel decoding in the THz band is more critical than that in lower bands. In this sense, low-density parity-check (LDPC) codes are a good choices due to their inherently parallel decoding scheme. On the other hand, frequency nonstationarity in the THz band demands a flexible coding rate and code word. In this regard, turbo and polar codes are preferred instead. Therefore, turbo, LDPC, and polar codes are all potential candidates for THz communications [10]. The feasibility of achieving terabits-per-second data rates using polar codes was investigated by using an efficient majority logic-aided successive cancellation decoding algorithm. An implementation of a fully pipelined iteration-unrolled turbo decoder was reported with a throughput of more than 100 Gb/s.

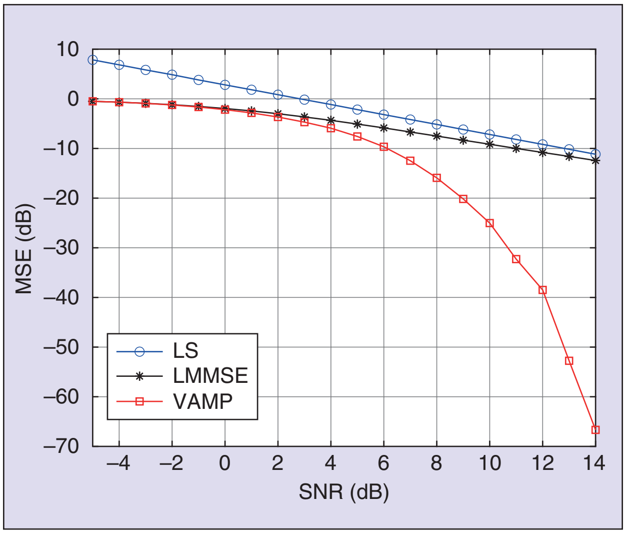

Figure 5 A performance comparison among different detection chemes. VAMP: vector AMP.

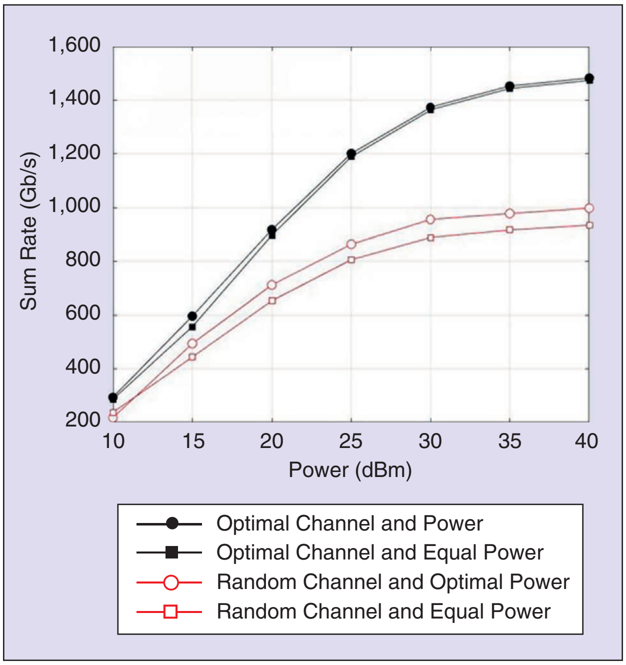

Figure 6 The sum rate versus the transmit power of the access point in a typical WLAN scenario.

THz Symbol Detection

Over the THz band, an antenna array is more compact compared with that in a lower band system. As a result, higher correlations among antenna elements are expected, and nonlinear symbol detection schemes are preferred for satisfactory performance [10].

Compressed detection was investigated for pulse-based THz communications [10]. A first-order Gaussian derivative pulse was used. The channel was identified via the orthogonal matching pursuit algorithm. With the channel estimation, a correlator-based detector was then implemented. Simulation results verified the superiority of the proposed channel estimation and detection scheme.

To demonstrate the advantage of nonlinear detection, an example of quaternary phase-shift keying transmission over Proakis-A channels is studied. In Figure 5, the detection performances of conventional LS and LMMSE approaches and emerging vector AMP (VAMP)-based method are compared. Clearly, the VAMP detection significantly outperforms conventional schemes, especially at high SNR, which is attributed to the nonlinear iterative mechanism of the original VAMP algorithm [12].

THz Resource Management

Radio resource management (RRM) is an important issue in THz communication systems. The peculiarities of the THz spectrum bring some challenges and opportunities for solving the RRM problem. On the one hand, the ultrahigh communication frequency of THz EM radiation makes THz communications suffer from not only the high free-space loss but also the molecular absorption loss in the atmosphere. As a result, the path loss of THz communications is highly frequency selective and strongly depends on the distance. The transmission distance is strictly constrained. The very small wavelength enables the integration of a large number of antenna elements on chip with the current size, and it is possible to realize a ultramassive multiple-input, multiple-output (MIMO) system. The corresponding beam-forming and nonorthogonal multiple access (NOMA) techniques could also be adopted in THz communication systems.

Due to its ultralarge bandwidth and ultrahigh data transmission rate, a THz system can support wireless local area networks (WLANs), indoor cellular networks, wireless backhaul communication, and nanocommunication. In different scenarios, the objectives of RRM may be different. We consider a typical WLAN scenario and propose a resource management scheme to maximize the sum rate of all users while satisfying the minimum rate requirements of users. Numerical simulation results are shown in Figure 6. Some typical application scenarios are illustrated as follows.

WLANs

In THz-based WLANs, the main objectives are to increase the coverage and achievable data rate. In [13], a hybrid beam-forming scheme with distance-aware MC transmission was designed. An adaptive power allocation and low-complexity antenna subarray selection policy was developed to serve different users at varying distances.

Indoor Cellular Networks

At present, the RRM of indoor cellular networks in THz communication mainly includes the integration of ultramassive antenna arrays and NOMA because beam-forming solutions can help expand the communication coverage, and NOMA greatly supplement this by gathering more users on a very-wide-frequency band. Through the joint optimization of beam, bandwidth, power, and other resources, the MIMO–NOMA system can simultaneously meet both massive connectivity and extremely high data rates in THz communication.

Wireless Backhaul Communication

Wireless backhaul communication refers to the communication between small base stations in small cells or ultradense networks. In these scenarios, the objectives of RRM are usually to maximize the network throughput with the quality of service (QoS) guaranteed. In [14], the problem of concurrent transmission scheduling for a THz wireless backhaul network was investigated. An algorithm of QoS-aware bandwidth allocation and concurrent scheduling was proposed to increase the weighted sum of completed flows with their QoS requirements and higher system throughput.

Nanocommunication

THz communication can also be used in some small-scale scenarios, like nanocommunication. The authors in [15] studied the joint design of nanonode association and resource allocation in a hierarchical nanocommunication network with multiple in-body nanonodes and micronodes. The authors formulated a weighted energy efficiency optimization problem and decomposed the joint problem into network clustering and resource allocation problems. The resource allocation problem was solved by using continuity relaxation theory and an improved dynamic programming method to determine the frequency and power. As a result, a distributed joint network clustering and resource allocation algorithm was proposed.

DISTANCE-ADAPTIVE MODULATIONS WILL BE PURSUED, ESPECIALLY AT LONG DISTANCES, DUE TO THE UNIQUE BAND-SPLITTING PROPERTY OF THZ COMMUNICATIONS.

Future Research Challenges

THz Channel Modeling

The existing THz channel measurements are mainly operated at 300 GHz, and most of them are conducted in indoor scenarios or short-range transmission. In the future, these measurements at higher frequency bands are necessary for the development of THz channel models. In additional, the scenarios also need to be expanded into outdoor or some specific scenarios.

Artificial intelligence (AI) is a promising technology in THz channel modeling. By constructing large numbers of channel measurement/simulation databases, we can explore the complex relationships among channel characteristics and frequency bands, scenarios, and system configurations. Machine learning regression algorithms are used to predict the channel characteristics in the future, at unknown frequencies and in novel scenarios, based on the channel measurement/simulation databases.

THz Multibeam Antenna

Fully integrated multibeam THz antennas that can provide multipolarized beams, e.g., dual linearly and dual circularly polarized, are of great interest for future applications. In addition, efficient shared aperture methods and structural designs should be investigated, which can greatly shrink the form factor of the front-end module. Moreover, new materials and processing techniques are another important aspect to be explored; these should be targeted to further loss reduction and the low-cost yet accurate implementation of THz antennas.

THz Front-End Chip Design

The conventional wisdom for RF front-end design is splitting, optimizing, and then assembling. This classical method has significantly benefitted electronics. Nevertheless, at THz frequencies, this approach shows

APPLYING MACHINE LEARNING TO THZ RRM CAN FURTHER IMPROVE THE SPECTRUM AND POWER UTILIZATION AS WELL AS OBTAIN MORE EFFICIENT AND INTELLIGENT SOLUTIONS.

its inherent limitation. To address this critical issue, FCI is expected to deeply and inherently integrate EM-field-based passive designs with active circuits. In the foreseeable future, FCI-based THz chips may involve and expand to a wide scope.

THz Baseband Signal Processing

Distance-adaptive modulations will be pursued, especially at long distances, due to the unique band-splitting property of THz communications. This incurs extra complexity and is undesirable in applications demanding low power consumption, e.g., a nanonetwork. Low-order and noncoherent modulations are possible solutions since spectral efficiency is not a critical issue over the THz band.

Accurate channel state information is the key for precoding and beam forming. Channel estimation and tracking in the THz band can be very challenging in mobile scenarios, where a slight variation can incur a large change in the channel state. Furthermore, high-dimension optimization problems have to be solved to obtain the precoding and beam-forming matrices, as THz systems are expected to be doubly massive MIMO [10].

THz Resource Management

The management of networks and services will face great challenges, such as network traffic, resource and big data management, and energy efficiency. Therefore, new technologies and strategies are needed to deal with these issues in a more efficient and intelligent way. Machine learning is an emerging field of the AI-assisted network, and it is one of the effective solutions for managing large amounts of data. It is very advantageous to use machine learning to optimize resource allocation so that the network can meet the expected demand based on parameters, such as the location, time, and specific service requirements of individual users. Applying machine learning to THz RRM can further improve the spectrum and power utilization as well as obtain more efficient and intelligent solutions.

In THz communication, the varying QoS requirements of a large number of users and different services will generate a large amount of data. Data-driven machine learning can incorporate contextual information into the decision-making process of dynamic resource allocation optimization. Machine learning algorithms can allow the network to adaptively utilize different frequency bands and other diverse resources according to the locations and times of different users to meet different levels of data link requests and other specific service requirements.

Realization of THz Communication

In addition to the five specific technologies discussed, there are many new technical problems that need to be further solved. In particular, the core components used in THz communications need further breakthroughs in performance and working methods. Another huge challenge is THz system integration to promote expansion to more fields. However, there is no doubt that THz communication technologies will play an increasingly important role in military and civilian applications.

Conclusions

In this article, a comprehensive system-level survey of the key technologies in 6G THz wireless communication systems has been presented, mainly covering THz channel modeling, multibeam antenna design, front-end chip design, baseband signal processing algorithms, and resource management schemes. These technologies can provide a strong guarantee for the implementation of THz communication systems. Future research directions on these key components in 6G THz wireless communication systems have also been pointed out.

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