3D Network Modeling for THz-Enabled Ultra-Fast Dense Networks: A 6G Perspective

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ABSTRACT
Terahertz (THz) communications are envisioned as a critical technology for 6G and enable ultra-fast dense networks with tiny cells. Implementing THz-enabled ultra-fast cells requires new techniques due to its 3D nature. Stochastic geometry is a tool that is widely used for network deployment, which provides tractability and feasibility. In this article, we provide a summary of 3D network modeling for the THz system. We discuss the new 6G ultra-cell scenario along with a potential 3D network architecture. Several recent developments in network modeling applying a stochastic geometry-based clustered process are also presented. We also discuss several potential network modeling techniques such as Poisson Voronoi (PV) tessellation, Thomas cluster process (TCP), and Matérn cluster process (MCP). Subsequently, a 3D network model for THz-band ultra-cell is demonstrated. Finally, we discuss major KPIs for 3D stochastic geometry and conclude with research challenges and open issues for 3D THz architectures.

INTRODUCTION
The world is now embarking into the beyond fifth generation (B5G) or sixth generation (6G) mobile communications epoch [1], which will be wholly digital, enabling smartly enhanced mobile broadband connectivity and intelligent infrastructures to cater for the foreseen upsurge in mobile data. For example, it is expected that the total world traffic in mobile devices monthly will be about 164 exabytes (EB) in 2025,1 which is more than five times the traffic in 2019 (about 33 EB). Among various data traffic, video will be predominant. The lion’s share of mobile traffic is already made up of video traffic. For instance, in 2019, a significant portion of mobile traffic was video (63 percent), which is foreseen to increase in the coming years (e.g., the prediction is about 76 percent in 2025).2 This trait will continue to flourish even after reaching the 5G milestone in 2020, with B5G/6G mobile networks expecting to hold up significantly higher capacity (throughput) per device (up to terabits per second).

Deployment of dense ultra-fast small cell technology is widely envisioned for enhancing the spectral and energy efficiency of 6G networks to meet the foreseen market demand. However, merely reducing the cell size within the current sub-6 GHz and millimeter-wave (mmWave) spectrum band represents a short-term solution, where available spectral opportunities are limited and will certainly dry up. So where do we look next? 6G research stakeholders are currently drilling for spectrum in the higher frequency bands, spurring the onset of terahertz (THz) technologies [2] in an attempt to unlock vast swathes of the available spectrum representing a long-term solution to spectrum demand and entertaining the possibility of terabits per second. Is the future 6G landscape only about new spectrum?

A United Nations urbanization study1 indicates that urban areas are projected to increase in population and density in large magnitude rapidly between now and 2050, with about two-thirds of Earth’s population placed in urban areas by that time. This implies a far-reaching and profound communication phenomenon, where more and more devices will be connected in complex, dense urban environments with, for example, skyscrapers and high-rise infrastructures. In this context, the B5G/6G landscape aims to build on the initial 5G deployment phase (2020), envisioning an ultra-dense network of THz-based small cells (ultra-cell) that goes beyond legacy two-dimensional (2D) deployment and aims to provide 5G services to high-rise buildings and high-altitude platforms. This will require mobile stakeholders to review the way current mobile networks are modeled and deployed for optimizing B5G/6G coverage. One of the methods is to model and deploy the mobile system in three-dimensional (3D) space.

Both THz and 3D architecture network modeling are touted as potential 6G enablers for the emerging mobile landscape [1, 3]. Table 1 presents a brief summary of 6G-enabling technology and architecture that includes THz and 3D network architecture.

ARTICLE CONTRIBUTION
This magazine article provides a brief survey of 3D network modeling for THz frequency enabled ultra-fast dense networks from the upcoming 6G communication system’s perspective, focusing on a stochastic geometry analytical tool. This survey demonstrates and promotes attractive 6G scenarios, 3D network architectures, and the significance of stochastic geometry for network modeling. Moreover, it presents a comprehensive description of the different clustered process deployment while discussing 3D modeling for 6G THz ultra-cell. Several significant open issues are also highlighted for future research of the THz system.
ARTICLE ORGANIZATION
The rest of the article is organized as follows. A primer on 3D architecture and the 6G scenario is provided. Afterward, we describe the mathematical tool — stochastic geometry — for network modeling and its relevant state of the art (SoTA). The 3D network modeling technique for 6G THz-enabled dense ultra-cell networks is discussed. Primary performance metrics for stochastic-geometry-based 3D network modeling are provided. Finally, we highlight the research challenges and open issues, while the conclusions follow in the last section.

PRIMER OF 6G ULTRA-FAST SMALL CELL AND 3D NETWORK ARCHITECTURE
In this section, we describe two essential components of THz-based 3D network modeling:
• Ultra-fast dense THz-enabled small cells (ultra-cell)
• 3D network architecture

ULTRA-FAST THz-ENABLED SMALL CELLS (ULTRA-CELLS)
Among many, two primary criteria of 6G are:
• More bits, more spectrum, and more reliability
• From 2D areal to 3D volumetric system efficiency — spectral and energy efficiency (SEE)
  [1, 3]
To satisfy these criteria of 6G requires enormous data rates, and a more diverse and distinctive network architecture than 5G, thus motivating further exploration in carrier frequencies above 6 GHz. The volumetric bandwidth definition of 6G will be increasingly associated with 3D network architectures rather than the 2D spatial (areal) network. This incorporates the advancement of sub-THz mmWave technologies (mobile mmWave) that will become established in initial 6G systems as an initial step. As the research exploration of 6G advances, utilizing frequencies beyond mmWave will become necessary at the THz band. To make use of higher THz frequencies, the 6G cell size should reduce from small cells to ultra-cells whose radius is limited to only a few tens of meters [3]. This prompts novel architectural designs that require much denser deployments of ultra-cells. 6G ultra-fast tiny cells are deployed as indoor small cells in buildings, such as skyscrapers, office, school, and home, and outdoors coexisting with macrocells. The base stations (BSs) of the macrocell is called 5G next-generation NB (gNB). An unmanned aerial vehicle BS (UAV-BS) can be used as both a standalone macro BS or a small cell access point (AP). Figure 2 demonstrates a potential 6G ultra-fast scenario with dense small cells.

3D NETWORK ARCHITECTURE
Studies of cellular networks mostly assume unrealistic hypotheses such as 2D wireless networks. In fact, 2D models are tractable and very suitable for macro BSs (MBs) in the terrain of rural or suburban landscapes. However, they are insufficient for dense urban areas, especially the small cells deployed in high-rise buildings, infrastructures, and so on. These models cannot describe the system specificities, mainly the actual distance between the BS and user equipment (UE). It is crucial to expand models with realistic constraints to improve the system model and gain from the accuracy of analytical expressions. 3D space modeling of cellular networks offers realistic and accurate system models. Therefore, the 3D network architecture is of fundamental importance to efficiently evaluate future mobile networks such as 6G.

Furthermore, previous generations including 5G, have been modeled and developed to cater for predominantly 2D space; that is, network APs are deployed to provide connectivity and services to devices on the ground. Conversely, we envision future 6G heterogeneous network (HetNet) architectures to furnish 3D coverage, thereby accompanying terrestrial platforms with non-terrestrial infrastructures/devices (e.g., UAVs and satellites). Thanks to incorporating non-terrestrial (airborne) and terrestrial networks, communications in 3D space must be an integral part of 6G, including serving UEs in 3D and deploying 3D BSs (e.g., UAVs-drones, which can also be used as temporary BSs). 3D network modeling significantly varies from legacy 2D networks to a great extent thanks to the additional dimension (altitude/height) and the related degrees of freedom, and provides a platform for innovative system optimizations for mobility management, routing, and resource management [3].

Figure 3 shows a top view of a 3D network architecture with the THz-enabled spectrum. The ground distance or 2D distance between UE and transmitter is defined by the distance between the UE and the ultra-cell transmitter’s projection,
which is situated on the top of the building, onto the ground denoted by $d_{2D}$. The Euclidean distance or 3D distance between UE and 3D transmitter is then presented by

$$d_{3D} = \sqrt{d_{2D}^2 + a^2}$$

where $a$ is the altitude/elevation/height of the transmitter.

**STOCHASTIC GEOMETRY**

**TECHNIQUES FOR NETWORK MODELING: STATE OF THE ART**

Stochastic geometry is the primary mathematical tool that is widely used for communication systems modeling. Stochastic geometry is a branch of probability theory that can be used to describe the behavior of random configurations, including random networks, random cluster processes, and so on. Stochastic geometry is proficient for studying wireless networks, since the coverage probability, interference, signal-to-noise ratio (SNR) distribution, and system capacity are sensitive to nodes’ locations. It also offers, in most cases, expressions in closed form for the spatial component of wireless systems. This section will highlight the SoTA of several types of stochastic geometry processes that can be used for 3D THz wireless communication modeling. Stochastic geometry has already provided some viable evidence that point processes can indeed model so-called “repulsion and attraction” for transmitter deployments within a bounded space. However, current studies are limited toward conventional 2D space deployments, and there are no clear models for characterizing very small THz-enabled cells. At present, there are few studies that characterize 3D mobile deployment approaches in practical simulation environments let alone small cell (THz) deployment in 3D space for 5G/6G networks.

Urban network deployments are distinctively non-flat, but the de facto approach from stochastic geometry treats all transmitters and receivers as placed on a 2D plane [4]. In stochastic geometry network models, tiers of BSs are modeled as independent point processes, mostly the homogeneous Poisson point process (PPP) [5], the key benefits being mathematical tractability. However, a network model with a homogeneous distribution profile will show no spatial correlation between objects/points, resulting in unrealistic models that deviate from practical network deployments. In fact, multi-tier networks offer both repulsion and attraction properties between points: small cell clustering shows properties of spatial attraction between transmitter points to represent coverage for user-centric hotspot areas, while macrocell coverage must show a degree of repulsion to minimize interference, in addition to being a more representative profile for rural environments. Stochastic geometry as a tool has been shown to cater for these specific instances, by resorting to non-PPP approaches. The Ginibre PP (GPP), under the umbrella of determinantal point processes, can provide repulsion between nodes by varying the Beta function, which controls the degree of repulsion. It has been successfully applied to cellular networks in urban and rural environments [6, 7].

Clustered PPs (e.g., the Neyman-Scott process, Gaussian-Poisson process, PCP) have been applied to model spatial coupling (attraction), making them suitable for modeling a high density of users accessing hotspot areas [8–10], achieving a good trade-off between modeling accuracy and tractability. Reference [11] investigates the inhomogeneous Poisson point process (I-PPP), where the intensity function depends on distance leading to an interconnected, tractable, and feasible methodology for modeling cellular networks that exhibit both spatial clustering and/or repulsion. However, I-PPPs require definition of the distance-dependent intensity function, whose choice is challenging as no a priori information on its structure currently exists. Although stochastic geometry is a well-known statistical tool for modeling cellular networks; it is fairly unknown at present in terms of SINR distribution, coverage probability, and rates achieved in dense urban deployment of cellular networks based on small cell technology at THz frequencies that are sensitive to blockages and exploit highly directional 3D beam patterns. Moreover, many of the spatial distribution principles of stochastic geometry extend to “3” dimensions [12], but their extension to urban areas is challenging because of the deployment of users and infrastructure in an inhomogeneously distributed manner.

**3D NETWORK MODELING TECHNIQUE FOR 6G THZ-ENABLED DENSE ULTRA-CELL NETWORKS**

Legacy mobile systems are modeled resorting to stochastic geometry, which treats all transmitters and receivers as living on a 2D plane [4]. In this context, the PPP is the most widely applied approach for modeling a network deployment and deriving the coverage probability, which holds a significant edge in terms of mathematical tracta-

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**Table 1.** The traits of THz and 3D network architecture as 6G enablers [1].

| 6G enabling technology | Potential | Challenges | Use cases |
|------------------------|-----------|------------|-----------|
| New spectrum→THz       | Vast contiguous bandwidth, miniature antenna size, more focused beams | Hardware design, propagation loss such as molecular absorption loss | Ubiquitous connectivity (MBRLLC), tactile telepresence (mUURLC), holographic (mUURLC), Industry 4.0 (mUURLC) |
| Novel network architecture→3D network | Ubiquitous coverage in 3D space, uninterrupted service | Network modeling, optimization of topology, coverage probability, system efficiency such as energy efficiency | Ubiquitous connectivity (MBRLLC), digital healthcare system (mUURLC), mobility of unmanned devices (mBRLLC) |

Mobile broadband reliable low-latency communication (MBRLLC [3]), massive ultra-reliable and low-latency communication (mURLLC [3]). These are 6G use cases envisioned in [3].
The PPP is a point process model where the number of transmitters (or access points, APs) in a given area in 2D space or in a given volume in 3D space has a Poisson distribution with mean \( \lambda \), where the parameter \( \lambda \) denotes the density of the APs per unit area for 2D or per unit volume for 3D. However, the PPP method assumes one fundamental and inherent basic premise in that the mathematical objects are distributed randomly in space.

However, actual typical networking models comprise multilayer HetNets, where the BS models demonstrate different degrees of interactions among the locations in terms of repulsion and attraction: in small cell networks, there tends to be attraction reflecting user-centric hotspot areas, while there will be repulsion noticed at the macrocell level to represent the deployments of rural/urban scenarios. This distinction will stand out more in ultra-dense small cell environments. In this context, it is pretty evident that the trusted PPP techniques will not represent a precisely B5G/6G networking environment, and until now has been restricted to the 2D plane. The interesting research question that arises is how to model a multilayer deployment for the B5G/6G cellular environment, including the spatial dependencies for intra-tier small cell clustering in 3D space.

Poisson Voronoi (PV) [13] tessellation is very important for modeling 3D multilayer networks integrating ultra-fast dense small cells. We define the PV cell by edges labeling and differentiating the random coverage area of a given cell [14]. The probability density function (PDF) of the size of a typical 3D PV cell is calculated through the Monte Carlo method [13] and is given as follows [13, 14]:

\[
f_Y(y) = \frac{5^5}{\Gamma(5)} y^4 \exp(-5y) \tag{1}
\]

where \( Y \) is a discrete random variable that refers the magnitude of a regular PV cell which is normalized by the reciprocal of the dense ultra-cell density \( \lambda \), and \( \Gamma(x) = \int_0^\infty \exp(-t)t^{x-1} \) is the gamma function [14].

In 3D stochastic geometry, a typical user is deployed where the properties of the spatial Poisson cluster process (PCP) can be computed. It provides accuracy and tractability to network modeling. In other words, “the typical user is assumed to be representative of all users. Most of the properties of a 3D wireless networking deployment can be expressed as a function of the distance between the THz access points (TAPs) and the UE” [14]. Hence, the distance from the typical user to the nearest network nodes is of special significance in the stochastic deployment modeling of wireless networks [14].

There are several PCP methods available to create 3D network modeling. Among all the PCP, two methods are standout, widely used, and easily tractable for deploying purposes. Those are the Thomas cluster process (TCP) and Matérn
penetration-sensitivity to different types of blockages, and the utilization of extremely directional 3D beam patterns.

**MAJOR PERFORMANCE METRICS FOR STOCHASTIC-GEOMETRY-BASED 3D NETWORK MODELING**

There are several key performance indicators (KPIs) available to test and verify the results while deploying 3D stochastic geometry. In this section, we explain the two major KPIs that directly reflect and provide an accurate characterization in the modeling of the 3D THz ultra-cell scenario. These metrics are “primarily associated with either the SINR distribution that translates into ‘coverage/success probability’ or the ‘rate coverage’” [14].

**Coverage/Success Probability:** The coverage probability is determined as the probability that the SINR of a randomly selected UE is higher than a certain SINR threshold. In particular, this KPI tests whether the link quality is good enough for a successful connection. That is why the coverage probability is also called success probability [14]. Conversely, it can also be defined as an outage probability where the distribution probability of the SINR falls below a minimum pre-defined threshold. Therefore, the outcome of the SINR distribution is a phenomemonal characteristic to measure this KPI.

**Rate Coverage:** In ultra-cell systems, rate coverage is specified as the probability that the obtainable rate of an arbitrary typical UE is above a certain threshold [14]. In ultra-cell, rate coverage and SINR distribution are interlinked. Moreover, SINR distribution in rate coverage is also used to characterize independent cells’ load, backhaul capacities, and energy efficiency.

**RESEARCH CHALLENGES AND OPEN ISSUES**

A few research challenges and open issues need to be addressed for modeling a 3D THz-band wireless system. In this section, we try to highlight those critical research challenges in brief.

**3D Channel Modeling and Optimization for THz Bands**

So far, very limited channel models are available for THz frequencies, especially for those higher than about 300 GHz or outdoor mobile scenarios. Since THz bands and mmWave bands share certain similarities, an extension of the 3GPP new channel model can be studied as a baseline. In addition, the research community might consider propagation modeling of THz networks in a quasi-static manner in a hybrid model (i.e., a combination of stochastic and map-based models) to address THz channel characteristics. The major challenges lie in the presence of users and BSs harnessing 3D channel modeling. Specific features such as blockage, molecular absorption, scattering, and impact of different surfaces and materials need to be investigated on top of the hybrid model. Furthermore, the developed 3D channel models will need to be optimized for different THz-wave bands to support efficient initial access and beamforming/tracking using different frame structures and numerology. Moreover, novel 3D

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Figure 3. Top view of a 3D THz network architecture.
THz channel models are required that relate the stochastic properties of the radio channel to the underlying geometry of the 3D network architecture. Moreover, terabit-per-second baseband modulation and demodulation, and effective baseband algorithms also need to be investigated.

**Novel Information-Theoretical Analysis for 3D THz Networks**

5G waveforms — filter bank multicarrier (FBMC), universal filtered multicarrier (UFMC), and generalized frequency-division multiplexing (GFDM) — have the potential of inherent robustness against hardware impairments, reduction of signaling overhead, and good adaptability to mmWave or microwave propagation characteristics. However, for the higher THz band, the requirements on the hardware and channel propagation properties are different. Thus, a new waveform suitable for different THz mobile scenarios needs to be developed. Moreover, the research community need to find the novel theoretical capacity (the maximum achievable rates for single channels or network capacity) by informational-theoretical analysis of the various candidate spectrum bands with and without constraints, such as energy efficiency, the nonlinearity of an amplifier, analog-to-digital conversion (ADC) resolution and peak power, and multiple antennas with or without channel state information (CSI). Energy efficiency in bits per Joule can be used to derive coherent and non-coherent channels by using information theory tools.

**Mobility in 3D THz Networks**

Mobility is perhaps the single most challenging and most daunting problem for 3D THz-based cellular networks, and the one most often raised by prominent skeptics. It is easy to understand why, in the context of the large beam steering gains needed to overcome the propagation losses. These gains require highly directional and/or adaptively tuned patterns that hold only for a small 3D angle in space. As the UE moves around, it must either rapidly switch beams or adapt the current beam. The feedback and latency requirements are very challenging. Mobility can be viewed as the cause of decorrelation. The mobility challenge lies in the large beam steering gains required to overcome the propagation losses at THz frequencies. These gains require highly directional and/or adaptively tuned patterns that hold only for a small 3D angle in space. In fact, the requirement for (nearly) unrestricted mobility is arguably the key feature of cellular networks. Therefore, the need to model and observe the impact of mobility is necessary to quantify mobile network performance and provide a basis for designing new algorithms/protocols. Therefore, in the first instance, a model is required to emulate user mobility in small cell deployment. Many such models have been proposed, but nearly all have significant drawbacks. They either provide reasonable accuracy or simplicity/tractability, but never both. Mobility support is mostly studied through simulation studies, and cellular systems are still designed to support mobility primarily through iterative trial and error approaches. Almost nothing is known about supporting mobility in THz networks since THz applications have been limited to personal/local area networks, or for line-of-sight (LoS) point-to-point communications. Furthermore, future emerging deployment scenarios will be 3D, adding another challenging dimension to the problem.

**System-Level Evaluation for B5G/6G Networks**

Simulations are pivotal for research and standardization. At this stage, although prototypes naturally deliver the most reliable results, they are typically not available, and testing different candidate features would be too expensive. In this context, exploiting a commercial system-level simulator to emulate and validate the analytical 3D network models for THz-based small cells is also an option. Simulations often rely on empirical models for characterizing the propagation channel. However, ray tracing can be used to plot the channel characteristics taking into account diverse physical phenomena including reflections, diffractions, and diffuse scattering for very specific channel environments, including 3D deployments. The initial step might be to use a commercial ray-tracing tool to implement new signal coverage maps, which will replace the baseline system-level simulation (SLS) channel models to provide enhanced simulation accuracy.

**In-Flight Broadband Connectivity**

The advantages offered by 6G communications will not only be restricted to terrestrial systems. In fact, several foreseen 6G scenarios and business cases extend toward the skies, where in-flight broadband connectivity (IFBC) will also become a commodity in the mid-long term. In fact, there were some 1.103 billion passengers served in
A 3D THz-band wireless ultra-fast small cell network will provide in-cabin service. The system constitutes a hybrid connectivity platform that raises significant challenges in terms of delivering ultra-fast networks aligned with the 5G and 6G KPIs, and thus helping to overcome connectivity issues based on different regulatory frameworks across different countries.

**CONCLUSION**

In this article, we provide a brief survey of 3D network modeling for the THz system including addressing key research challenges as we enter the 6G era. We discuss the new 6G ultra-cell scenario along with the associated 3D network architecture. Several recent developments of network modeling applying a stochastic-geometry-based clustered process are also presented. We also discuss several potential network modeling techniques such as Poisson Voronoi tessellation, the Thomas cluster process, and the Matérn cluster process. Subsequently, a 3D network model for THz-band ultra-cell is demonstrated. Finally, we discuss major KPIs for 3D stochastic geometry, and conclude with research challenges and open issues for 3D THz architectures.

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