中国6G重磅论文推荐

6G愿景、需求和技术趋势：如何应对系统覆盖率、容量、用户数据速率和移动速度的挑战

临菲信息技术港

原文：

"Vision, Requirements, and Technology Trend of 6G: How to Tackle the Challenges of System Coverage, Capacity, User Data-Rate and Movement Speed"（ 6G 愿景、需求和技术趋势：如何应对系统覆盖率、容量、用户数据速率和移动速度的挑战），IEEE Wireless Communications, Accepted for Publication，（IEEE Early Access Articles）

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推荐理由：

该文对 6G 进行了全面探讨，包括愿景以及需求、技术趋势和挑战，旨在应对覆盖率、容量、数据速率和移动速度的挑战，提出了 6G 标准今后的发展方向。

作者是大唐移动高级研究人员、电子科技大学和北京邮电大学著名教授，该文是中国通信界关于 6G 研究的代表。

以下文字是小编对原文要点的理解，同时对一些技术点（例如 OAM）也补充了简要说明。

6G 愿景与需求

Vision and Requirements of 6G

覆盖

更深度和更广泛的覆盖。

频率

更高的频率，更宽的带宽，如毫米波、太赫兹、可见光等。

网络

结合人工智能的个性化智能网络，实现虚拟化个人移动通信。

安全

内生安全方案或功能安全集成设计，自我意识、实时动态分析、自适应风险和信任评估等。

融合

计算、导航、传感与通信融合，包括卫星通信，卫星导航和定位系统，甚至包括雷达传感系统。

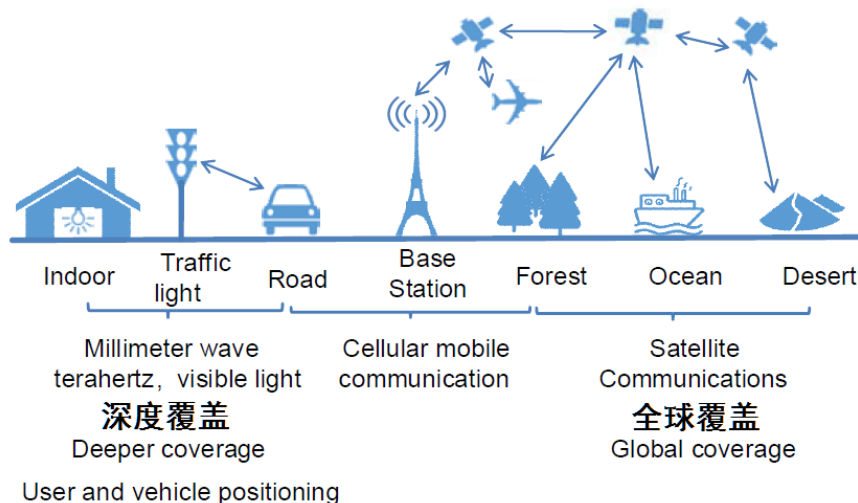### 智能

万物互联产生海量数据；与云计算、边缘计算、人工智能、区块链等结合；实现万物智能和群体智能，支持智能移动社会。

图 1 6G 全球覆盖和深度覆盖示意图

应用场景和能力
Application Scenarios and Capabilities Of 6G

应用场景

除了 eMBB、mMTC、URLLC 场景外，还将出现新的应用场景，例如：全息通信、个人监控、无人机的士（drone taxi）、机器人互联网、无线脑机交互等。

能力

与 5G 对比，6G 可能具有的能力见下表。

Major factors 主要指标	6G	5G
Peak data rate 峰值速率	> 100Gb/s	10[20] Gb/s
用户体验速率 User experience data rate	> 10Gb/s	1Gb/s
Traffic density 流量密度	> 100Tb/s/km²	10Tb/s/km²
Connection density 连接密度	> 10million/km²	1million/km²
Delay 时延	< 1ms	ms level
Mobility 移动性	> 1000km/h	350km/h
Spectrum efficiency 频谱效率	> 3x relative to 5G	3~5x relative to 4G
Energy efficiency 能量效率	> 10x relative to 5G	1000x relative to 4G
Coverage percent 覆盖率	> 99%	About 70%
Reliability 可靠性	> 99.999%	About 99.9%
Positioning precision 定位精度	Centimeter level	Meter level
Receiver sensitivity 接收灵敏度	< –130dBm	About –120dBm

技术趋势与挑战
Technology Trends and Challenges

6G 可用 3 个"新"和 3 个"ing"来描述。

6G 及 6G 后的关键技术和方法

扩展覆盖：地面和卫星移动通信的集成

传统上，地面移动通信和卫星移动通信是独立的，具有各自的标准，未来会将二者整合。低地球轨道（LEO）卫星通信近年来受到了广泛关注，但仍然存在一些挑战：

- 多普勒频移及其变化
- 传输时延
- 星间链路传输技术

新频谱资源及其利用

太赫兹和可见光频段

太赫兹通信和可见光通信面临的技术挑战：

太赫兹

- 硬件组件
- 信道建模与估计
- 定向网络

可见光

- 带宽扩展
- 非线性补偿
- MIMO

认知无线电和智能频谱共享

- 智能动态频谱接入
- 智能频谱共享
- 智能共生无线电（Intelligent Symbiotic Radio）

新的调制资源：OAM

利用轨道角动量（OAM）的无线通信是近几年的一个研究热点。上世纪 90 年度初证实了 OAM 的存在。2007 年，瑞典空间物理研究所通过仿真验证了可以使用相控阵天线产生具有轨

道角动量的电磁波（即涡旋电磁波），提出了利用涡旋电磁波增加无线通信容量的设想。

OAM 可以作为一种新的调制资源。不同的 OAM 模式是相互正交的，因而可以复用，为增加 6G 系统容量（以及增强其它关键指标）提供了一条新的途径。

OAM 无线通信的实现，需要解决三个关键问题：

- OAM 的波束发散限制了远距离应用
- 非视距条件下的建模与传输
- 收发两端失调（misalignment）情况下多种 OAM 模式的区分

提升系统容量：去蜂窝及 UUDN

去蜂窝（de-cellular）网络架构以及相应的以用户为中心的超密集组网（UUDN，User-Centric Ultra-Dense Network），适用于 mmWave、太赫兹、可见光等高频段，面临的挑战：

- 网络架构设计
- 移动性管理
- 干扰管理
- 资源管理
- 安全管理

新增能力：计算和集成人工智能

在 6G 中部署计算和 AI，存在的主要挑战有：

- 云、边缘和终端之间的协同智能和计算
- 异构性和动态融合
- 边缘 AI 硬件限制

新核心网：三维架构和智能移动管理

新的三维核心网

地面系统网络节点与卫星系统网络节点组成三维核心网络。

智能移动性管理

由于卫星的加入，带来移动性管理的新挑战。
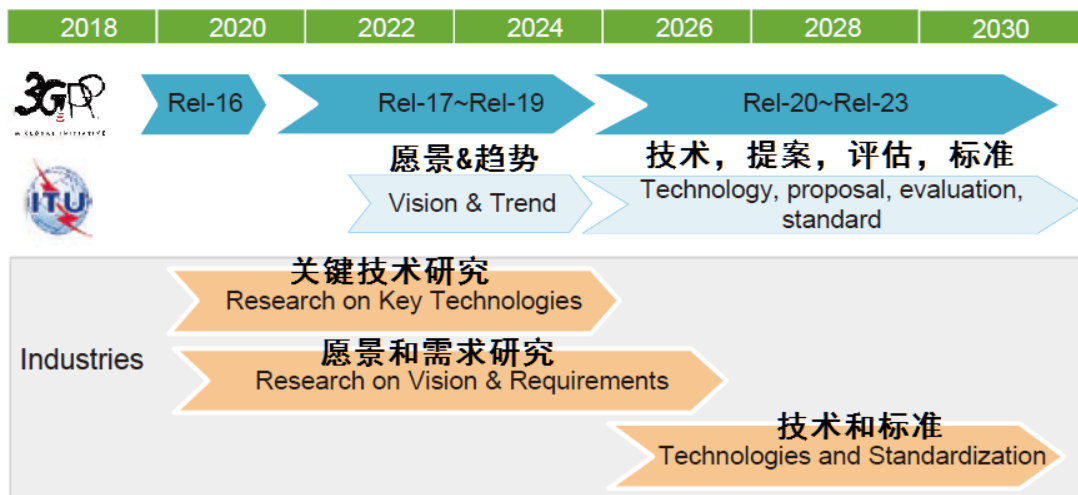
高效网络资源利用

无线资源的统一、高效分配，按需管理，控制不同的网络。

协议互操作性

地面网络和卫星网络应具有互操作性，以满足无缝传输。

6G 标准化路线图建议

世界各国学者和业界已经开始 6G 愿景、需求和关键技术的研究，预计在 2024 年至 2026 年间将趋于一致，然后是 6G 的标准化工作。

6G 路线图见下图所示。

6G 路线图

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附：论文原文（见文后）

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6G 候选技术研究专家系列专访(一)——轨道角动量技术

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面向未来 5G/6G 的毫米波通信研究现状及进展

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Vision, Requirements, and Technology Trend of 6G: How to Tackle the Challenges of System Coverage, Capacity, User Data-Rate and Movement Speed

Shanzhi Chen, Ying-Chang Liang, Shaohui Sun, Shaoli Kang, Wenchi Cheng and Mugen Peng

Abstract

Since 5G new radio comes with non-standalone (NSA) and standalone (SA) versions in 3GPP, research on 6G has been on schedule by academics and industries. Though 6G is supposed to have much higher capabilities than 5G, yet there is no clear description about what 6G is. In this article, a comprehensive discussion of 6G is given based on the review of 5G developments, covering visions and requirements, technology trends and challenges, aiming at tackling the challenge of coverage, capacity, the user data rate and movement speed of mobile communication system. The vision of 6G is to fully support the development of a Ubiquitous Intelligent Mobile Society with intelligent life and industries. Finally, the roadmap of the 6G standard is suggested for the future.

Introduction

Mobile communication systems upgrade to a new generation in every 10 years. In particular, research on a new generation will formally start right after the earlier generation is standardized. For the present fifth generation (5G) mobile communication system, the standard for the non-standalone (NSA) version was finished at the end of 2017 and a standalone (SA) version was finalized in the middle of 2018 by the 3rd Generation Partnership Project (3GPP). Though further enhancements for 5G new radio (NR) are still ongoing, research on the next generation, namely 6G, has been discussed by academics and industry. For example, in the European Union, some research projects such as Terapod and Terranova were sponsored by 5GPPP Phase 1 in 2017, then more projects were followed in Phase 2 and Phase 3 aiming at 6G innovations. In the U.S., following the joint university microelectronic project (JUMP) launched by the Defense Advanced Research Projects Agency (DARPA) in 2016, the frequency band from 95GHz to 3THz was granted by the Federal Communications Commission (FCC) for research on 6G. Also, in the Chinese Communication Standardization Association (CCSA), two study items were launched in 2018,

one focusing on the vision and requirements of 6G and the other on the key technologies for 6G. To better understand 6G and for the benefit to do research on 6G, based on the review of the present 5G, this article tries to discuss a series of key issues on 6G, including vision and requirements, technology trends and challenges, as well as a roadmap, and so on.

The rest of this article is organized as follows. In the following section, the progress of 5G development is reviewed, and the vision and requirements of 6G are discussed. Then, the key technologies of 6G are discussed. Following that, we highlight the roadmap of 6G development. In the final section we give our conclusions.

Vision and Requirements of 6G

Review of 5G Development

To review the process of 5G, the pace of the development is fast. For example, in 2013, different organizations were launched and various white papers were issued. In 2014, a vision and requirements for 5G were defined by ITU. In 2015, key technologies were identified by academics and industry. In 2016, standardization was formally launched in 3GPP, and also technology trials were conducted by major official organizations. In 2017, the first version NSA standard was finished. In 2018, the second version SA standard was finalized. In 2019, a 5G pre-commercial network is under development widely in the world.

The vision and requirements are defined by ITU: 5G should satisfy three typical scenarios and eight key performance indexes (KPIs) [1]. Challenging technical indicators of three scenarios include Gb/s data rate of enhanced mobile broadband (eMBB), millisecond (ms) air interface delay of ultra-reliable low latency communication (URLLC), and one million connections per square kilometer (1M/km^2) of massive machine type communication (mMTC). To satisfy these KPIs, a series of enabling technologies were proposed and discussed in standardizations and implemented in technology trials [2]. Wireless technologies include massive MIMO, advanced coding and modulation, mmWave communica-

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tion, non-orthogonal multiple access, ultra-dense networking (UDN), dual connectivity architecture, flexible frame structure, and so on. Network technologies include network slicing, mobile edge computation (MEC), software defined network (SDN), network function virtualization (NFV), customized mobility, service based architecture, and so on. Unfortunately, at the moment, there are two different aspects between definitions and actual realizations. One comes from the progress of 5G NR standardization; scenarios of eMBB and URLLC have been included in the 5G NR NSA and SA versions, while the mMTC scenario has not been agreed into NR yet being represented by narrow band Internet of Things (NB-IoT). The next comes from the progress of 5G industry development, the scenario of eMBB is given higher priority and has developed much faster than the other two scenarios URLLC and mMTC. Reasons are difficulties occurring when pushing forward these IoT related scenarios, such as diversified, fragmented, and unclear requirements, and so on. In conclusion, superior to former generations, 5G brings the groundbreaking aims of interconnection of everything (IoE) and breaks through the traditional layout of mobile communication. It has met a series of challenges from standardization and implementation, and so on. Since it is difficult to solve all related problems in the 5G stage, 5G can be regarded as just the starting phase of IoE. Therefore, research beyond 5G will aim to remove those differences between definition and realization and then surpassing the existing vision and requirements.

Here we give further explanations. Just as the developing experiences from former generations, 2G is the best solution for voice mobile communication though voice was earlier defined in 1G, and similarly 4G is the best solution for mobile Internet though mobile Internet was earlier defined in 3G. There comes a magic word "1G short, and 2G long, 3G short, and 4G long." What will be the lifetime of 5G? The goal of 5G is to solve the interconnection of everything (IoE), but 5G vertical applications (Internet of Vehicles, Industrial Internet, and so on) is a very difficult and long-term process. IoE may thus only be the early idea from 5G technology experts, yet many issues are not clear at the moment, such as: What will be the future actual demands? What will be the 5G pain points for industry application? What will be the industrial ecology? These key issues challenge 5G's ability to satisfy IoE, which is actually what 6G needs to solve. It is rather like imperfect 3G fulfilled by 4G.

Now, the users volume of former generations (mainly 2G, 3G, and 4G terrestrial mobile communication networks) is about 70 percent of the wordwide population. Due to the costs and technology limitations, those networks cover only about 20 percent of the global land area, and less than 6 percent of the earth's surface. For example, more than 80 percent of the land area and 95 percent of the sea area of China are not covered by terrestrial mobile communication networks. Since 5G is originally defined as a terrestrial mobile communication, it will also meet the above radio coverage limitation. That is to say, to make everything interconnected, future mobile communications should cover the entire surface area of the earth, including oceans, deserts, forests and airspace.
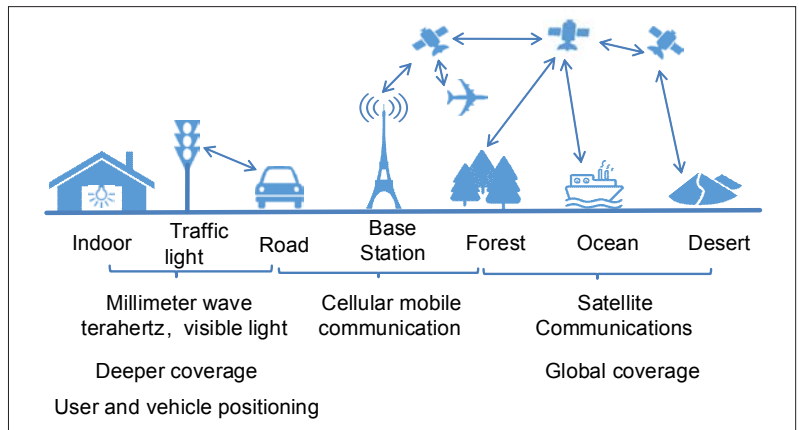

FIGURE 1. 6G with global and deeper coverage.

THE VISION AND REQUIREMENTS OF 6G

From the above analysis of 5G developments, it can be foreseen that on one hand 6G should solve the limitations of 5G including at least system coverage and IoE. On the other hand, to meet the mobile communication demands of the year 2030 and beyond, 6G should make the human society as a *Ubiquitous Intelligent Mobile Society*. This becomes the vision of 6G.

Based on the vision and 5G development, 6G will be further upgraded and expanded to achieve 10 to 100 times higher data rate, higher system capacity, higher spectrum efficiency, lower delay, as well as wider and deeper coverage, to support higher moving speed, to serve the interconnection of everything, and to fully support the development of a Ubiquitous Intelligent Mobile Society for intelligent life and industries. The following paragraphs will give detailed descriptions of foreseen requirements related to the vision.

First, 6G should be a ubiquitous and integrated network with broader and deeper coverage, including terrestrial communication, satellite communication, device to device communication in short range, and so on. With intelligent mobility management technology, 6G can serve in various environments such as airspace, land and sea, realizing a global ubiquitous mobile broadband communication system, as shown in Fig. 1.

Second, 6G is expected to work on a higher frequency to achieve wider bandwidth, such as mmWave, Terahertz, visible light, and so on. Compared with 5G, 6G can promote a data rate up to 10 to 100 times, supporting Tb/s peak data rate and 10Gb/s user experience data rate. In addition, 6G can use flexible frequency sharing technology to further enhance the frequency reuse efficiency.

Third, 6G is a personalized intelligent network. Combined with artificial intelligence technologies, 6G will realize virtualized personal mobile communication, with the network changing from a traditional function centralized type into a novel 3-centralized type, that is, user centralized, data centralized, and fully content centralized.

Fourth, the 6G network will have an endogenous security scheme or function security integrated design. By introducing trust and safety mechanisms, 6G has the capability of self-awareness, real-time dynamic analysis, and adaptive risk and confidence evaluation, all of which will help realize cyber space security.

Major factors	6G	5G
Peak data rate	> 100Gb/s	10[20] Gb/s
User experience data rate	> 10Gb/s	1Gb/s
Traffic density	> 100Tb/s/km^2	10Tb/s/km^2
Connection density	> 10million/km^2	1million/km^2
Delay	< 1ms	ms level
Mobility	> 1000km/h	350km/h
Spectrum efficiency	> 3x relative to 5G	3~5x relative to 4G
Energy efficiency	> 10x relative to 5G	1000x relative to 4G
Coverage percent	> 99%	About 70%
Reliability	> 99.999%	About 99.9%
Positioning precision	Centimeter level	Meter level
Receiver sensitivity	< −130dBm	About −120dBm

TABLE 1. Possible capabilities of 6G in comparison with 5G.

Fifth, 6G will merge computation, navigation and sensing with communications. For example, 6G will include not only satellite communication systems, but also satellite navigation and positioning systems, and even radar sensing systems. 6G will adopt a more open architecture, with software defined core network and radio access networks; 6G can realize fast and self-intelligent development and rapid dynamic deployment of network functions.

Finally, 6G can generate massive data through Internet of everything; also, 6G can combine with novel technologies such as cloud computing, edge computing, artificial intelligence, block chain, etc.; 6G can realize everything intelligence and group collective intelligence (swarm intelligence); and 6G can finally support a Ubiquitous Intelligent Mobile Society.

APPLICATION SCENARIOS AND CAPABILITIES OF 6G
With the above expected vision and requirements, 6G will have much wider application scenarios than that of 5G. Scenarios include not only traditional eMBB, mMTC, URLLC scenarios, but also many upcoming ones, such as holographic communication, personal monitoring, drone taxi, Internet of robots, wireless brain-computer interactions, and so on. Similar to that, virtual and augmented reality (AR/VR) is one of the most important applications of 5G; holographic communication will be one of the most important applications of the high throughout requirement of 6G. It is expected that ten years later (2030), media interaction will be developed from the current plane multimedia to high fidelity AR/VR, and finally to wireless holographic communication.

To show the 6G capabilities, Table 1 tries to give a comparison between 6G and 5G. Comparing original KPIs defined in 5G [1], 6G is expected to have 10 times enhancement on data rate, density and energy efficiency. 6G is expected to have about three times enhancement on mobility and spectrum efficiency; and 6G is expected to further decrease its latency to be below 1 millisec-

ond. Also, for those newly defined KPIs, 6G will enhance coverage percentage from the present 70 percent to 99 percent; 6G will improve reliability from the present 99.9 percent to 99.999 percent; 6G will reduce the positioning error from the present meter level to the centimeter level; and 6G will even improve the receiver sensitivity better than −130dBm, and so on.

TECHNOLOGY TRENDS AND CHALLENGES
The challenges of 6G include system coverage and capacity, user data rate and movement speed, spectrum and energy efficiency. To follow up the listed challenges, 6G can be represented using "6" key aspects, including three "new" resources and methods and three "ing"-related key technologies in Fig. 2.

The realistic way to solve the problem of global coverage and higher-speed user movement is to adopt a satellite mobile communication system. Compared with a terrestrial mobile communication system, a satellite mobile communication system can achieve wider coverage (such as over-the-sea, forest, and desert) at low cost. When the moving speed of a mobile terminal is beyond Mach level, it is difficult to be supported by the terrestrial mobile communication system; yet it is easy to be supported by satellite mobile communications. Since 6G will integrate land wireless mobile communication, medium and low orbit satellite mobile communication, and also short range direct communication technologies into one mobile system, there are thus challenges to design a new core network architecture and mobility management.

There are four methods to enhance 6G system capacity. The first is to add more spectrum bandwidth. The second is to increase the spectrum efficiency of the air interface (bits per second per Hertz) by adopting better modulation and channel coding, or new modulation resource. The third is spectrum reuse by reducing the cell size. The fourth is new spectrum utilization, such as flexible spectrum sharing technology. Ways to offer user data rate mainly come from the first two methods in the list from one to four for system capacity.

In addition, 6G will develop the new air interface that enables multiple heterogeneous wireless transmission accesses, and 6G will merge computation, navigation and sensing, both of which will make 6G a much more complex system, requiring AI technology and computing capability to empower 6G.

In-depth analysis of some of these listed technologies are elaborated below.

EXPENDING COVERAGE: THE INTEGRATION OF TERRESTRIAL AND SATELLITE MOBILE COMMUNICATION
The prospect of future global communication networks is to offer fast and integrated service to ubiquitous users with on-demand personality at any time. Satellite communication has advantages to support system coverage and user moving speed, and it will play an important role in the 6G infrastructure.

According to the height of orbit, satellites can be classified as low-earth orbit (LEO) satellite with height about 500 to 2000 km, medium-earth orbit (MEO) satellite with height about 2000 to 36000 km, and geostationary (GEO) satellite with height about 36000 km.

FIGURE 2. Key technologies and new methods for 6G and Beyond.

Conventional terrestrial and satellite mobile communication systems were established with separate standards in ITU. They have different characteristics as shown in Table 2. For example, at the 3G stage, three kinds of CDMA systems, CDMA2000, WCDMA and TD-SCDMA, were approved for terrestrial mobile communication, while eight systems, SRI-A to SRI-H, were approved for satellite mobile communication. Similarly, at the 4G stage, following LTEs were approved as 4G terrestrial mobile communication standards in WRC-12; SAT-OFDM and BMSat were also approved by ITU as 4G satellite mobile communication standards [3] in September 2013.

To go beyond 5G and to integrate satellite mobile communication into terrestrial mobile communication, 3GPP started a study item (SI) in RAN1 of Release 15. The SI discusses channel modeling and design constraints and analyzes influences to NR. A technical report, TR38.811 *Study on NR to support Non Terrestrial Networks* (NTN), was formed eventually in 2018. In consecutive release, a further SI, Solutions for NR to support Non Terrestrial Networks, was conducted in 3GPP, trying to explore technique solutions.

For a satellite communication system, usually the LEO system is given the widest attention and regarded as the hottest topic in recent years. Due to lower orbit height, compared with MEO or GEO, LEO has priorities like shorter transmission delay, smaller path loss, and so on. Furthermore, thanks to the state of the art satellite technologies, multiple satellites can be launched together by one rocket, the total cost for a satellite system is much reduced. With hundreds or thousands of satellites located at dozens of orbits above the earth, the LEO system can thus authentically realize global coverage and more efficiency by frequency reuse. In addition, advanced mobile technologies provide technique guarantee for the success of the LEO system, such as cellular communication, multiple access, spot beam, frequency reuse, and so on. Therefore, the LEO system is deemed as the most prospective satellite mobile communication system.

However, there also exists some inherent disadvantages in the LEO system, for example, the large number of satellites induces higher complexity in control, operation, and management. Furthermore, from the communication aspect, there meets integrating challenges for LEO and terrestrial systems.

Major factors	Satellite mobile communication	Terrestrial mobile communication
Link type	Including service link and feeder link	Service link only
Transmission distance	Above 600km	About 1 km
Transmission delay	Tens to hundreds millisecond	us to ms level
Frequency	Usually high frequency band like Ku, Ka, Q, etc	Usually low frequency band below 6GHz
Path loss	Often above 180 dB	Usually within 140 dB
Doppler shift	Up to several hundred KHz	Usually within KHz level
Cell Radius	Often several hundred km	Usually 300–500 m
Mobility	Frequently happen, including inter-beams (inter-cells), inter-satellites, inter-gateways.	Inter-cells only
Requirements for PAPR	Strictly low PAPR to avoid power waste	Low PAPR
Frequency reuse	Different frequencies with reuse factor 4,8, etc.	Same frequency with reuse factor 1.

TABLE 2. Differences between terrestrial and satellite mobile communication systems.

Major challenges are listed in the following paragraphs.

Doppler Shift and Doppler Variation: Since a LEO satellite moves much faster than the earth rotation, it brings evident Doppler shift and Doppler shift variation in communication. Taking the orbit height 600km as an example, the Doppler shift reaches up to 480KHz at Ka-band 20GHz carrier, which will seriously affect the communication process like synchronization, random access, signal measurement, signal detection, and so on.

Large Transmission Delay: Since the satellite transmission distance is much longer than that of terrestrial transmission, the LEO signal transmission delay and the path loss are much higher than that of terrestrial systems, resulting in non-negligible differences in designs on aspects like waveform, modulation, channel coding, HARQ, MAC, RLC, and so on. For example, due to power limitations from the satellite, the waveform and modulation should be redesigned to make the PAPR as low as possible. Due to larger delay for signal transmission, HARQ

The LED bandwidth can be enhanced by various methods such as blue filtering, pulse shaping and subcarrier equalization. It is desirable to develop more advanced transmitter pre-equalization and receiver post-equalization techniques to address the modulation-bandwidth limitation of VLC systems.

should be redesigned to adapt to the satellite transmission.

Transmission Technology for Inter-Satellite Link (ISL): Usually there are two types of communication modes from satellite; one is the bent-pipe mode, and the other is the regenerative mode. For the regenerative mode, a satellite has the functions of detection, demodulation and modulation on communication signals. Even the routing function can be included in satellites; thus, satellites can communicate with each other directly via the inter-satellite link (ISL). ISL will stimulate research on innovative transmission technology, for example, optical communication and Terahertz (300GHz-10THz) radio communication are important research directions in recent years. When Laser and Terahertz are used for ISL, they can provide high date rates up to several Gb/s, to ensure the requirements of capacity and throughput. An ISL transceiver has advantages of small size, light weight, low power consumption, strong ability to resist electromagnetic interference, and high security and confidentiality. However, due to the narrow beam in transmission and high moving speed, it is tough for ISL beam searching, targeting, capturing and tracking. In addition, since an ISL has long transmission distance, the signal attenuation is heavy, resulting in challenges on receiver sensitivity, signal detection quality, and receiving performance.

New Resource and Utilization Method Of Spectrum

Terahertz and Visible Light Band: The utilization of the still-unregulated high-frequency band can alleviate the spectrum scarcity and capacity limitations of current wireless communication systems. The Terahertz (THz) band (from 0.1 THz to 10 THz) and visible light band (from 400 THz to 800 THz) are recognized as two ultra-wide spectral bands to enable ultra-high-rate communications. The corresponding THz communications and visible light communications (VLC) are two promising technologies for 6G and beyond [4].

On the one hand, THz communications rely on advanced THz devices to transfer information at THz band. Currently there are two kinds of THz communication systems, including solid state THz communication system based on a frequency mixing mechanism, and a spatial direct modulation THz communication system, which modulates baseband signals directly into a continuous THz carrier wave. THz communications have diverse application scenarios, such as the indoor wireless mobile networks supporting holographic video conference and virtual reality, nanoscale communication networks for health monitoring via nano-machines, and space communication networks like inter-satellite communication and near-space communication.

Although THz communications have obvious advantages for 6G and beyond applications, there are still many technical challenges to be solved before practical deployment.

High-Frequency Hardware Components: For solid state THz communication systems, it is difficult to design efficient radio-frequency (RF) circuits such as THz mixers, THz oscillators, THz amplifiers and THz antennas. Specifically, it is a great challenge to design ultra-broadband THz antennas with

high gain and fast beam scanning function. Physically, the low noise design for such high bandwidth super-heterodyne transceivers is also a worldwide challenge. For direct modulation THz communication systems, one determining factor is the performance of the THz modulator. Specifically, it is desirable to design an amplitude THz modulator with high modulation speed and depth, as well as a phase modulator with large scale and linear phase shifts. The advanced materials and device structures such as GaN-HEMT and Graphene are promising for THz modulator design [5].

THz Communication Channel Modelling and Estimation: To implement efficient wireless communication systems in the THz band, it is imperative to establish accurate channel models for THz communications. Different from lower-frequency channels, THz channel modelling needs to consider several unique factors, including the highly frequency-selective path-loss due to the absorption loss of oxygen and water-vapor molecule, mutual coupling effect and near-field effect together with spatial non-stationarity over ultra-massive antenna arrays. It is thus desirable to have efficient channel estimation schemes with low computing load for THz communication systems with ultra-massive antenna arrays.

Directional Networking for THz Wireless Communication: Though the beams of the THz band are relatively narrow compared with lower frequency bands, the directional antenna is still preferable for THz communication networking, since it is capable to concentrate the THz wave energy in a particular direction to support longer-distance communication, and to reduce interference toward the neighboring nodes. The challenges for THz-band directional networking include efficient neighbor-discovery algorithms under time asynchronous system, topology control algorithms with optimized trade-off between node degree and jump stretch, and multiple-access-control (MAC) protocol with higher access capacity and lower resource consumption.

On the other hand, VLC are realized by transmitter performing intensity modulation (IM) on devices such as light-emitting diodes (LEDs). The VLC receiver performs direct detection (DD) on the received light by a silicon photodiode. VLC can achieve gigabits-per-second transmission with commercial LEDs through downlink. VLC have a variety of applications such as indoor high-speed data links for personal area networks, outdoor vehicle-to-vehicle and vehicle-to-infrastructure communication, and RF not friendly environments like mines and underwater networks [4]

Despite VLC having inherent advantages such as ultra-wide frequency band, high energy efficiency, low cost and better safety, compared to traditional communication systems, VLC still faces the following technical challenges:

Bandwidth Enhancement: Commercial LEDs typically have very limited modulation bandwidth and slow modulation response, which directly limit the achievable data rate of VLC systems. The LED bandwidth can be enhanced by various methods such as blue filtering, pulse shaping and subcarrier equalization. It is desirable to develop more advanced transmitter pre-equalization and receiver post-equalization techniques to address the modulation-bandwidth limitation of VLC systems.

Non-Linearity Compensation: Orthogonal frequency-division multiplexing (OFDM) is widely considered as the most powerful modulation technique for high-speed VLC. The relationship between the current through LED and the emitted light of an LED is inherently nonlinear. Hence, the LED's limited dynamic range and the high peak-to-average-power ratio constitute the main challenges for OFDM-based VLC systems. Sophisticated pre-distortion and post-distortion methods are expected for OFDM to counteract the effect of the nonlinearities.

Multiple-Input Multiple-Output (MIMO) Techniques: MIMO techniques are alluring to enhance the VLC rate, but MIMO systems are difficult to realize in VLC. First, the diversity gains are limited due to very similar paths between the transmitter and the receiver. Second, the design of VLC MIMO receivers is difficult. A non-imaging receiver requires accurate transmitter-receiver alignment, while an imaging receiver suffers from lower sampling rate of the imaging sensor. Interference-mitigation techniques in VLC MIMO need to be further studied, such as multiuser precoding and coordinated-beamforming [6].

Cognitive Radio and Intelligent Spectrum Sharing: Although new ultra-high-frequency bands from THz and visible light will be explored in 6G and beyond, the available spectrum resource, especially the lower-frequency band with established coverage, is still scarce in terms of exponential growth of wireless data traffic. In 5G and previous systems, dedicated spectrum allocation makes the spectrum resource fully occupied, and the utilization rate is low. Hence, efficient spectrum managements are still critical schemes to improve the spectrum efficiency of 6G communication systems. Cognitive radio (CR) techniques allow multiple wireless systems to share the same spectrum by utilizing spectrum sensing and interference management techniques. In particular, the spectrum sharing techniques enable secondary systems to utilize the unlicensed or underutilized spectrum temporally and geographically, which will significantly enhance the spectral efficiency [7].

As one of the most recent evolutions of CR and spectrum sharing, symbiotic radio (SR) is a new promising technique for 6G communication systems. By using the technique, multiple subsystems of a heterogeneous wireless communication system intelligently cooperate with each other to realize mutually beneficial transmission and efficient resource sharing. The technique further enhances overall efficiency of a CR system significantly. One typical example is an SR network based on ambient backscatter communications [8], in which the IoT devices transmit information to their destinations by passively reflecting the signals received from the primary transmitter. The IoT transmission thus shares the same spectrum, signal source, and infrastructure of the primary system.

Despite the extensively studied conventional CR and spectrum sharing techniques, there are still critical challenges for new CR-inspired technologies including intelligent SR, efficient dynamic spectrum access, and intelligent spectrum sharing.

Intelligent Dynamic Spectrum Access: Complete information about the network state is typically required in order to obtain optimal dynamic-spectrum-access (DSA) policies. However, existing DSA protocols cannot effectively adapt to more complex real-world models. There are studies applying deep reinforcement learning for designing distributed DSA algorithms to learn the hidden patterns of the primary systems [9]. In order for the DSA algorithms to be applicable to complex spectrum sharing environments, new model-free distributed learning algorithms with lower computing overhead are highly desirable.

Intelligent Spectrum Sharing: A variety of spectrum sharing technologies can be used in 6G and beyond, such as device-to-device communication, in-band full-duplex communication, non-orthogonal multiple access, and spectrum sharing in unlicensed spectrum. To manage massive connections in 6G applications, distributed and efficient interference avoidance/mitigation techniques are required to enhance the system performance. The block chain and deep-learning technologies were initially shown to be efficient approaches for flexible spectrum sharing in [10]. Therefore, new frameworks and mechanisms for intelligent spectrum sharing need to be developed.

Intelligent Symbiotic Radio: SR is a new wireless communication paradigm, which aims to enhance the performance of the whole communication system via intelligent inter-subsystem cooperation. The subsystems may have different symbiotic mechanisms such as parasitism, commensalism and mutualism. Under each symbiotic mechanisms, it is desirable to investigate the theoretical limits of fundamental information and transmission theory with interference cancellation/mitigation/utilization. However, the research on SR is at the infant stage, and many open issues need to be addressed. For example, for large SR networks, wireless access and multi-dimensional resource allocation are also challenging, which need to be addressed via techniques such as artificial intelligence and big data analysis.

NEW RESOURCE FOR MODULATION: OAM

Along with the fast development from 1G to 4G, different orthogonal resources such as frequency, time, code, and space are extensively used. Although non-orthogonal multiple access was discussed to be promoted in 5G, it is more demanded and attractive to explore a new resource for significant spectrum efficiency, user data rate, and capacity enhancement in 5G-beyond and 6G wireless communications.

The electromagnetic wave has not only linear momentum, which is the foundation for the current wireless communications based on traditional plane-electromagnetic (PE) waves, but also angular momentum, which is being focused on recently. OAM, as a kind of wave-front with helical phase, can be used as a new resource for modulation in wireless communications [11]. Spacing OAM has a great number of topological charges, that is, OAM-modes [12]. Different OAM-modes are orthogonal with each other and can be multiplexed/demultiplexed together, bringing a new way for capacity enhancement in 6G and Beyond wireless communications networks.

Figures 3a–3c show the radiation pattern of OAM-modes 0, 1, and 2. Different data streams can be modulated on different OAM-modes. Figures 3d–3f plot the field intensity for different distances corresponding to different OAM-modes.

The research on SR is at the infant stage, and many open issues need to be addressed. For example, for large SR networks, wireless access and multi-dimensional resource allocation are also challenging, which need to be addressed via techniques such as artificial intelligence and big data analysis.

(a) Radiation pattern of OAM-mode 0   (b) Radiation pattern of OAM-mode 1   (c) Radiation pattern of OAM-mode 2

(d) Field intensity of OAM-mode 0   (e) Field intensity of OAM-mode 1   (f) Field intensity of OAM-mode 2
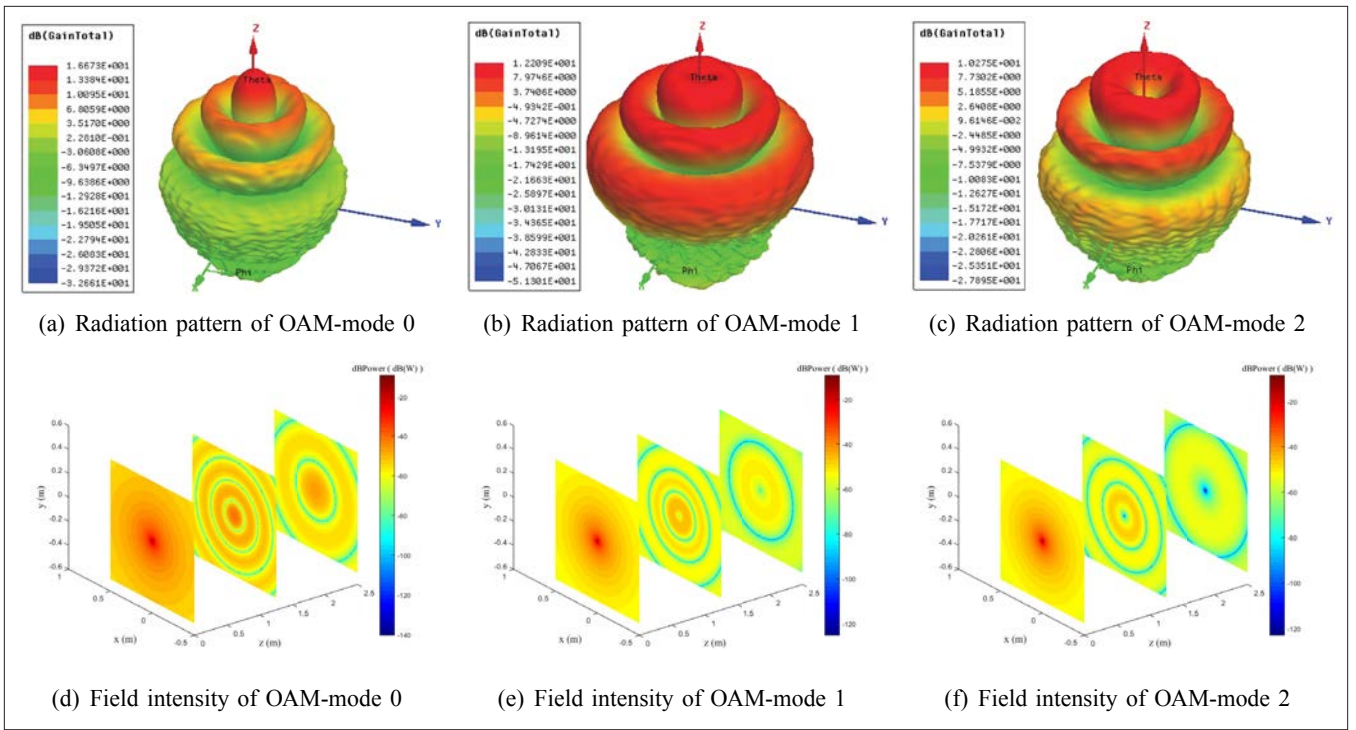
FIGURE 3. Radiation pattern and field intensity for OAM waves with OAM-modes 0, 1, and 2: a) radiation pattern of OAM-mode 0; b) radiation pattern of OAM-mode 1; c) radiation pattern of OAM-mode 2; d) field intensity of OAM-mode 0; e) field intensity of OAM-mode 1; f) field intensity of OAM-mode 2.

The OAM waves are centrally hollow except OAM-mode 0, which is in fact the traditional PE wave. The central hollow pattern increases as the order of OAM-mode increases, which indicates that the degree of divergence increases as the order of OAM-mode increases.

Although it is intriguing that OAM can greatly increase the capacity and enhance other key metrics for wireless communications, the following three critical problems need to be solved before its practical implementation.

Beam-Divergence: OAM beams are divergent, which limits the efficient reception and long-distance propagation in OAM based wireless communication systems. It is desired that OAM beams are convergent for efficient transmission. There exist tentative schemes for converging OAM beams such as antenna based anti-divergence. The antenna based anti-divergence schemes employ parabolic antennas or lens antennas to converge OAM beams [13]. However, with the decrease in degree of divergence, OAM beams, after antenna converging, are still with central hollow structure after relatively long-distance transmission.

Transmission: It is now commonly accepted that OAM can be used for line-of-sight (LoS) environments such as microwave backhaul scenarios and indoor massive data scenarios. For non-LoS (NLoS) environments, since the wave-front of OAM-modes changes with reflection and refraction of OAM waves, it is very difficult to model the OAM transmissions in fading scenarios. How to facilitate OAM based transmissions is an open problem for NLoS environments.

Transceiver-Misalignment: Due to the phase sensitivity of OAM waves, current detection schemes are generally proposed for the transceiver-coaxial scenarios. However, it is usually the case that the transmitter and receiver are misaligned with each other in practical wireless communications scenarios. The transceiver-misalignment makes it challenging for distinguishing multiple OAM-modes at the receiver. Some phases-turbulence compensation schemes have been proposed for OAM based transmission in transceiver-misalignment scenarios.

INCREASING SYSTEM CAPACITY: DE-CELLULAR AND UUDN

As mentioned in the beginning of this section, to enhance system capacity, typical methods are introducing more spectrum bandwidth resource and reusing of efficient spectrum by reducing the cell size, that is cell split. 6G is expected to work on higher frequency bands to achieve wider bandwidth, such as mmWave, Terahertz, visible light, and so on. Compared with 5G, the wireless coverage range of a 6G base-station (BS) or access point (AP) is thus getting even smaller. But it is impossible for the cell to split indefinitely, which approaches the limit of the system capacity improvement.

In the traditional cellular network, a single BS serves multiple users. The handover control occurs when a user crosses different BSs. When the number of APs approaches or even exceeds the number of user terminals as soon as the cell size and transmitting distance become smaller and smaller, the cellular network architecture becomes ineffective. In this case, the de-cellular network architecture was proposed [14]. This network will organize a dynamic APs Group (APG) to serve each user seamlessly without the user's involvement, and let the user feel like a network is always following them. In this case, the network will intelligently recognize the user's wireless communication environments, and then flexibly organize the required

APG and resource to serve the user. User-Centric Ultra-Dense Network (UUDN) was proposed in [14] correspondingly, which is a wireless network with comparable densities of access point (AP) and the density of users. The proposal introduces the philosophy of network serving user.

The de-cellular and UUDN are suitable for the higher frequency band, such as mmWave, Terahertz, visible light band, yet there are several challenges:

Network Architecture: How to design a network architecture to dynamically cooperate and transmit between APs, to match user's service requirement, to support continuous communication during its movement, and to enhance the spectrum efficiency and user experience. That is how to realize Dynamic network serving user.

Mobility Management: While a user is moving, its AP group will be dynamically adjusted or refreshed to support its movement. The Dynamic APs Grouping method (DAPGing) was proposed in [14] and needs to be much further explored.

Interference Management: Interference becomes more complex in the de-cellular network and UUDN. Dynamic ways such as Artificial Intelligence (AI) need to be introduced to solve such a complex problem.

Resource Management: The considerations of resource allocation should be based on users and a corresponding AP group, not based on single cell in traditional way.

Security Management: A new issue is the security mechanism among APs and AP groups. Trusted authentication and secure transmission should be built among APs, user to AP and AP groups. Because the AP group serving a user is generated dynamically, it is necessary to identify the security mechanism of the AP group when an AP joins or exits.

ADDING CAPABILITY: COMPUTING AND INTEGRATED ARTIFICIAL INTELLIGENCE

To realize the vision of 6G, current wireless networks should be changed and revolutionized from the traditional function centralized type into a novel user centralized, content centralized, and data centralized (3C) type. Thus, adding computing and AI capabilities to wireless networks is essential. In particular, to enhance transmit quality and decrease computing complexity for supporting ultra-wide spectral band in physical layer, to converge computing, communications, and data cache efficiently for achieving diverse performance, and to make the network architecture adaptive to ubiquitous application scenarios, AI is a trump card to extend the coverage, meet diverse requirements of massive applications, and improve performance significantly in 6G. Empowered by modern AI technologies, 6G can interconnect a massive number of devices from various environments, such as in the air, in space, on earth, and over the sea, and provide them unprecedented quality of service. In terms of applications, using AI for intelligent learning, inference, and decision making are just a few examples in 6G [15].

Although there are significant benefits, it is still challenging to achieve real deployment of computing and AI capabilities in 6G. Specifically, the challenges are mainly as follows.

Collaborative Intelligence and Computing among Cloud, Edge and Terminal: The first key question for 6G is "where to add the computing and AI capabilities, cloud or around edge?" When adding the computing and AI capabilities to the cloud, the resource-limited end-user devices can enjoy the benefits of rich computing power and storage in the cloud and edge; while posing heavy load on the backbone networks the load may result in the unpredictable transmission latency. On the other hand, when deploying the computing and AI capabilities on the edge, the load on the backbone networks can be alleviated and the transmission latency can be significantly reduced. However, the end-user devices may face too large computation latency due to limited computing power and storage on the edge if the MEC scheduling policy is poor. As a result, collaborative intelligence and computing among cloud, edge and terminal should be revealed with highest priority.

Heterogeneity and Dynamical Convergence: 6G is highly heterogeneous in terms of the device type, the occupied frequency band, the infrastructure type, and service type. Such heterogeneity makes it prohibitively difficult and expensive to intelligently coordinate the communication, data caching, and computing resources. For example, the fog-computing-based radio access network architecture has been proposed to make communication, data caching and computing converge efficiently through flexibly assigning communication, data caching and computing functions in different entities. Meanwhile, the intent-based radio access network has been presented to make the network architecture flexible and simple through software-definition and re-configuration for the ubiquitous intelligent mobile society with low cost. Therefore, it is anticipated that the dynamical convergence can be efficient through designing a software-defined and re-configured radio access network architecture, so that the communication, data caching, and computing can be dynamically re-organized.

Hardware Constraints on Edge AI: The effectiveness of edge AI algorithms often relies on the ever-increasing computing power of devices. However, 6G devices will be pervasive then they are with limited communication resource, computing power, and storage suitable for the internet of things applications. Applying the existing AI algorithms may result in the degradation of performance. To address this issue, novel and lightweight edge AI algorithms for 6G devices should be developed.

NEW CORE NETWORK: A THREE-DIMENSIONAL ARCHITECTURE AND INTELLIGENT MOBILITY MANAGEMENT

In the past, terrestrial mobile system and satellite mobile system are independent, and both are two-dimensional network architectures. From the technology perspective, 6G will integrate terrestrial wireless mobile communication, medium and low orbit satellite mobile communication and short distance direct communication technologies. At the same time, 6G will integrate communication and computing, navigation, perception, and other new technologies. 6G will thus establish a new three-dimensional (3D) core network architecture which can integrate those systems, and support global ubiquitous coverage of high-speed

Empowered by modern AI technologies, 6G can interconnect a massive number of devices from various environments, such as in the air, in space, on earth, and over the sea, and provide them unprecedented quality of service. In terms of applications, using AI for intelligent learning, inference, and decision making are just a few examples in 6G.
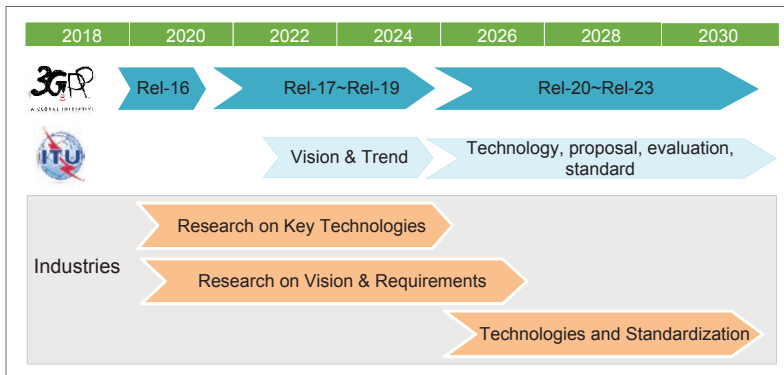
FIGURE 4. 6G roadmap.

mobile communications, including communications in the air, in space, on earth and over the sea, by leveraging intelligent mobility management and control methods.

Although this 3D core network architecture can break through traditional coverage limitations and eventually form an unprecedented universal coverage, there meet following challenges to be solved before it is really available.

New Three-dimensional Core Network: The 6G core network will be a three-dimensional network being composed of network nodes of a terrestrial system and network nodes of a satellite system. As part of the converged network, a satellite node will be a part of a serving core network through integrating some network functions into the satellite, such as Access and Mobility Management Function (AMF), Session Management Function (SMF), and User Plane Function (UPF). UE can establish the multiple Packet Data Unit (PDU) sessions through the terrestrial node and/or the satellite node by unified protocol. The 6G network is the service-driven intelligent network, and it can allocate the network resources dynamically according to the service requirements and user's priority. The 6G core network will dynamically establish the connections of the user plane following the global view of the network located on the terrestrial system and the satellite system.

Intelligent Mobility Management: The mobility management of 5G and pre 5G did not take network node movement into account. The fast moving satellites will bring new challenges to 6G, the mobility scenarios of 6G will become more complicated. The inter-satellite links change while satellite position changes. The movement will impact the network topology, handover control methods and so on. Fortunately, the trajectory of satellites is known due to the pre-determined ephemeris and should be used as an important input to 6G mobility management. The moving prediction of a terminal shall also be enabled by AI. For terminals with ongoing service connections, intelligent mobility management should tackle different types of handovers, such as handover between beams, handover between satellites, handover between airplane stations and satellite/earth stations, and handover between satellite and earth stations. The handover decision must consider the trajectory of satellites, the characteristics of users and infrastructures, for example, bandwidth, delay, signal strength of access links against the quality requirement of the on-going services, as well as load balance among satellites and terrestrial systems. The overall design of handover control procedure should consider the different signaling transmission delays of messages traversing the satellite and terrestrial links. For the terminals without connections, how to achieve reasonable trade-off between paging signaling cost and offered performance is also a challenge.

Efficient Network Resource Utilization: Based on the global coverage and overall coordination capability, multi-dimensional information should be processed effectively, wireless resources should be allocated uniformly and efficiently, and different networks should be managed and controlled on demand. Though terrestrial networks and satellite networks have different topologies and different stability in different scenarios, with the service-driven, intelligent, and three-dimensional core network, also with dynamic change between terrestrial and satellite networks will be hidden behind data transmission. Therefore, a user can get transparent access in the integrated network, and flexible roam between terrestrial access technology and satellite access technology.

Protocol Interoperability: In terrestrial networks, usually the TCP/IP protocol is used. In satellite networks, since the communication channel has ultra wide bandwidth, long transmission delay and higher bit error rate, the traditional TCP/IP protocol will face low efficiency due to its original design only for computer network. Therefore, the TCP/IP protocol needs to be optimized for satellite networks, or novel protocols such as delay tolerant network (DTN) protocol may be used. Since different communication protocols may be used for terrestrial networks and satellite networks, the heterogeneous network may experience multiple conversions between protocols, resulting in formidable challenges for the network integration. Therefore, different protocols should have interoperability, to satisfy seamless transfer between terrestrial networks and satellite networks.

ROADMAP SUGGESTIONS FOR 6G STANDARDIZATION

An expected roadmap for 6G is shown in Fig. 4. From the standards organization 3GPP, present release 16 for 5G NR will be finished in early 2020, the research on beyond 5G will thus be processed from release 17 to release 19, and research for 6G may be further followed by release 20. From the standards organization ITU, 5G standardization will be issued by the end of 2020, the research on 6G can then be started, with the vision and technology trends being considered first. Simultaneously, from the industry perspective, research on 6G has been started. Key technologies, visions and requirements are being discussed by academics and industry all over the world. It is expected that this research will continue until converging during the period 2024-2026, the standard work for 6G will then start and will work toward 2030.

In the 5G stage, close international cooperation was established to achieve a global standard. For 6G, cooperation should be enhanced further, not only covering present international cooperation from different countries and organizations, but also considering contributions from verticals even at the initial stage of 6G research. In addition, since new material for devices and equipment will be

challenged toward its theoretical limitation, there should be much closer cooperation among enterprises in the hierarchical industrial chain.

Conclusions

Following the standard optimization and pre-commercial stage of 5G, research on 6G has been under discussion gradually. Though there has not been any officially agreed opinion on what will be the 6G, as a future novel generation, 6G will no doubt have 10 to 100 times higher overall capabilities than that of 5G. From the technology perspective, 6G will integrate terrestrial wireless mobile communication, geostationary and medium and low orbit satellite communication and short distance direct communication technologies, as well as integrate communication, computing, navigation, perception, artificial intelligence and other new technologies. Standards work for 6G will take place around 2025 and a 6G pre-commercial network will be available around the year 2030. Finally, 6G will support the development of a Ubiquitous Intelligent Mobile Society with intelligent life and industries.

Acknowledgment

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In the 5G stage, close international cooperation was established to achieve a global standard. For 6G, cooperation should be enhanced further, not only covering present international cooperation from different countries and organizations, but also considering contributions from verticals even at the initial stage of 6G research.

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