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Towards 6G: Key Technological Directions

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Abstract

Sixth-generation mobile networks (6G) are expected to reach extreme communication capabilities to realize emerging applications demanded by the future society. This paper focuses on six technological directions towards 6G, namely, intent-based networking, THz communication, artificial intelligence, distributed ledger technology/blockchain, smart devices and gadget-free communication, and quantum communication. These technologies will enable 6G to be more capable of catering to the demands of future network services and applications. Each of these technologies is discussed highlighting recent developments, applicability in 6G, and deployment challenges. It is envisaged that this work will facilitate 6G related research and developments, especially along the six technological directions discussed in the paper.

Index Terms

6G, Intent-based networking, THz communication, AI, blockchain, smart devices, gadget-free communication, quantum communication

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***Abstract*—Sixth-generation mobile networks (6G) are expected to reach extreme communication capabilities to realize emerging applications demanded by the future society. This paper focuses on six technological directions towards 6G, namely, intent-based networking, THz communication, artificial intelligence, distributed ledger technology/blockchain, smart devices and gadget-free communication, and quantum communication. These technologies will enable 6G to be more capable of catering to the demands of future network services and applications. Each of these technologies is discussed highlighting recent developments, applicability in 6G, and deployment challenges. It is envisaged that this work will facilitate 6G related research and developments, especially along the six technological directions discussed in the paper.**

***Index Terms*—6G, Intent-based networking, THz communication, AI, blockchain, smart devices, gadget-free communication, quantum communication**

I. Introduction

Sixth-generation mobile networks (6G) are expected to be deployed by 2030 to facilitate advanced communication requirements of the future data-centric and hyper-connected society. 6G networks will reach extreme network capabilities to facilitate ultra-high-speed connectivity, ultra-low-latency communication, and highly scalable low-latency machine-type communication [1], [2]. Fig. 1 portrays the key improvements envisaged through 6G over fifth-generation mobile networks (5G), and a high-level 6G architecture, indicating the key technological components and applications of 6G. These network capabilities of 6G will enable many new applications and services, including holographic teleportation, energy internet, space and deep-sea communication, Connected Autonomous Vehicles (CAVs), and the next industrial revolution known as Industry 5.0. However, realizing 6G networks and 6G applications demands significant advancements over existing technologies. Many research articles on 6G, such as the work published in [2], [3], provide a broad overview of 6G vision and developments towards 6G. In contrast, this paper focuses on six technological directions towards 6G, namely, Intent-Based networking (IBN), Terahertz (THz) communication, Artificial Intelligence (AI), Distributed Ledger Technology (DLT)/Blockchain (BC), Smart Devices and Gadget-free communication (SDG), and Quantum Communication (QC). The paper elaborates on key technological developments, 6G applicability, technical challenges, possible solutions available in the literature, and possible applications of each of the six technological directions. The impact of these technological directions for 6G architectural layers is presented in table I, and 6G applications are tabulated in table II.

The rest of the paper is organized as follows. Section II explores IBN, whereas Section III focuses on THz communication. Section IV explains the technological direction of AI. Section V presents DLT/BC, Section VI portrays smart devices and gadgets and Section VII identifies quantum communication as key technological directions towards 6G. Furthermore, the technological developments under each direction, along with their potential, existing challenges, and possible solutions, are presented in table III. Finally, Section VIII concludes the paper. It is envisaged that this paper would shed light to facilitate future research and development work along these technological directions towards realizing 6G.

II. Intent-based Networking

IBN automates the deployment of business intent in networks by utilizing well-defined policies to support the rapid adaptation of new 6G services [4]. Due to the inherent support to realize business intentions, IBN is being adapted in the production networks of large enterprises. A typical IBN comprises three primary functions, namely intent translation, activation of intents, and assurance. Intent translation translates business into policies that can be understood by networks, whereas, activation of intents performs network-wide deployment of intent policies by automating the configuration across physical and virtual networking devices. In addition, assurance monitors and analyzes the network to verify the desired intent by using Machine Learning (ML) and AI. Currently, IBN deployments are built on Software-Defined Networking (SDN) where the SDN controller acts as a centralized control point to manage network operations. Thus, both network softwarization technologies (i.e., SDN/Network Function Virtualization (NFV)) and network intelligent technologies (i.e., AI/ML) are expected to play a vital role in realizing IBN in future networks.

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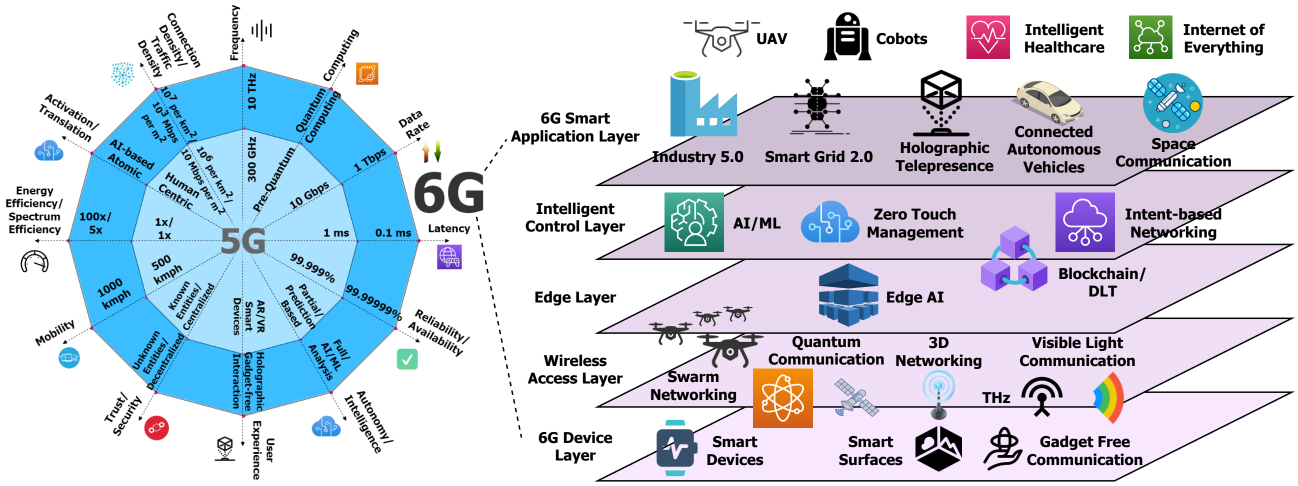

Fig. 1: 6G improvements, high level 6G architectural layers, 6G technologies, and applications [1].

A. 6G Applicability

IBNs are expected to introduce AI into 6G networks [5]. Accordingly, IBNs have the capability to solve many of the persisting issues with pre-6G networks, specially in the areas of flexibility, efficiency, and security. This is performed through transforming users' intents into network configurations and strategies. The use of AI and *Big Data* with IBN can improve the robustness, dynamicity, and adaptability in automated network operation and maintenance. IBN heavily depends on AI/ML to perform routine tasks, set policies, respond to system events, and verify achievement of goals and actions of each intent. Moreover, IBN-enabled 6G networks will support fast and easy deployment of new services, service prioritization, and service integration across all 6G Network layers (See table I). For instance, IBN helps to accurately identify multi-type end-user service intent in Internet of Things (IoT) applications and implement multi-dimensional sensing requirements. Also, the continuous monitoring, gathering of telemetry, and efficient analysis using AI/ML reduces the risk of malfunction of services and neutralizes other threats. Furthermore, IBN helps to optimize and configure the network services to achieve the goals of corresponding business applications. The intent translation in IBN allows the desired operational service-level agreements of users to be efficiently applied across the network and improve the customer experience. It fuels the use of 6G across many vertical industries. IBN systems can also intelligently predict possible deviations from the intent, and proactively take action to streamline with the intent. Thus, IBN enables self monitoring and self correcting features of 6G. In addition, IBNs can facilitate the massive demand for intelligent services in 6G, such as adapting to time-varying radio propagation and network environment banking on real-time network data [5]. Hence, IBN offers a clear advantages over regular networking to enable 6G applications, as seen in Table II.

B. Deployment Challenges and Possible Solutions

The current implementations and developments of IBN is mainly focused on the network core. Hence, IBN solutions are required to be optimized for the wireless access network. The availability of AI resources at the access network segment with Edge-AI and distributed AI will facilitate the deployment of IBN in wireless networks. O-RAN Alliance developed Non Real-Time RAN Intelligent Controller (Non-RT RIC) concept based on automation and AI/ML to realize Intent-based wireless RAN management. High degree of network programmability and intelligent automation of 6G RAN is possible to realize with Intent-based Non-RT RIC deployment [6]. In addition, considering the IBN integration with 6G from the very early stages will resolve possible integration challenges in the future. Use of IBN in 6G could also introduce new security challenges, such as, information exposure, undesirable configuration, and abnormal behavior attacks. Thus, network security solutions such as input validation via mutual authentication between intent producer and consumer, controlled access via authorization and AI-based proactive monitoring for abnormality detection, need to be in place before integrating IBN in 6G architecture. 6G wireless networks have many configurable parameters to support billions or even trillions of users and devices. However, the traditional IBNs will not have an agile operation system to keep up with such a huge user device ecosystem and the rapidly changing business needs in 6G networks. This can be addressed through AI/ML based automation. Furthermore, developments are needed towards a more flexible and accurate intelligent IBN to facilitate dynamic business models. In addition, choosing and optimizing AI algorithms to facilitate the efficient and accurate operation of IBNs also remain to be thoroughly explored [5].

III. THz Communication

While commercial 5G networks are deployed throughout the world, the research community is on the verge of speculating what will be future 6G systems. As discussed in [10], the key performance factors of 6G include peak data rate of 1

TABLE I: Impact of the technological directions for 6G layers [2], [7]–[9]

Technology Direction	High Level 6G Architectural Layers 6G Smart Application	Intelligent Control	Edge	Wireless Access	6G Device
Intent-based Networking	Rapid implementation of goals, network customization for applications	Better troubleshooting, resolution, analytics, reconfiguration, self-healing	Customized service delivery, automated and proactive service migrations, user level service assurance	Customized coding, intent based spectrum allocation, AI/ML RAN managemnet, innovation for openness	Map intents to device configurations
THz Communication	Provide high data-rate for indoor applications	Deployment of emerging services and control policies	High speed transmission between edge nodes, self-backhauling in tiny-cell networks	Tbps data rates with channel modelling, random access, and MAC protocols	Impact on the transceiver, antenna design, and network architecture
Artificial Intelligence	Intelligent data analytics for autonomous decisions	Autonomous control and operation of sensors and actuators	Intelligent routing and placement to optimize energy efficiency	Intelligent spectrum sensing, analysis, and allocation	Intelligent user devices and algorithms that process and analyze data at the local level.
DLT and Blockchain	Decentralized, secure, transparent and privacy-protected applications, BaaS for 6G applications	Security and privacy for sharing AI/ML training data and models for intelligent control	Trusted sharing of locally trained models in FL and decentralized decision making	Share access networks and spectrum, secure SDN-based operations, transparent radio management	On demand computational off-loading, incentive-based trading of extra resources
Smart Devices and Gadgets	Enable new interactions, powerful computing and strong connectivity	Contribute to edge intelligence capabilities	Harness/ contribute to edge intelligence capabilities	Support THz communication, quantum communication, VLC and LIS	Enable extended reality, holographic tele-presence, gadget-free communication
Quantum Communication	Seamless integration of smart societies over THz system with optical infrastructure	Faster optimization of problems and machine learning techniques in intelligent control systems	Realize fast and secure communication for serverless edge networks	Reshape wireless network via THz communication, enhance indoor and outdoor localization via fingerprinting	Facilitate quantum enabled secure communication to 6G devices

Tbps, experienced data rate of 10 Gbps, traffic density of 100 Tb/s/km^2, a latency of less than 1 ms, reliability of 99.9999%, centimeter-level positioning, and receiver sensitivity of less than -130 dBm. Several frequency bands used in the current network generation, such as millimeter Wave (mmWave) and Sub-6 GHz do not satisfy the growing demands in 6G. In this vein, THz communication (0.1 THz to 10 THz corresponding to the wavelength of 3 mm and 0.03 mm) is regarded as a promising solution thanks to its distinctive features. In particular, the THz band can provide up to a hundred GHz bandwidth, which far exceeds the mmWave band with 10 GHz bandwidth at most. THz communication is also highly suitable for massive multi-input multi-output (MIMO) systems with hundreds of antennas. Moreover, high directionality enabled by THz signals can be leveraged for interference mitigation and user satisfaction maximization [11]. Recent advancements in THz hardware and wireless technologies have shown the great impact of THz communication on 6G architectural layers (as shown in table I).

A. 6G Applicability

THz band have been used for traditional applications such as sensing, imaging, and localization [11]. Recently, THz communication has found in promising 6G scenarios, summarized in table II. Bandwidth-abundant THz channels are used for direct wireless transmissions between radio towers and mobile devices [9]. Furthermore, THz communication can be leveraged as a key enabler of integrated access and backhaul networks. In particular, THz communication enables wireless backhauling between macrocells and small cells. This THz-enabled wireless backhaul can be used on top of other frequency bands such as Sub-6 GHz and mmWave, and also eliminates the need for a licensed bandwidth spectrum. The implementation of wireless backhaul plays an important role in ultra-dense heterogeneous networks, where deploying wired backhaul for a large number of small cells and tiny-cells is an impractical solution. The existing satellite systems typically use Ku band, Ka band, and V band for Internet connectivity. For instance, the OneWeb satellite system has deployed a total of 110 satellites (December 2020) over the Ku and Ka bands at an altitude of 1200 km (https://www.oneweb.world). Using THz communication for high-speed satellite communication links is also a promising scenario in future networks [9].

B. Deployment Challenges and Possible Solutions

Despite distinctive features and promising applications, several challenges should be overcome for THz communication realization in 6G wireless systems. For instance, large path losses, and smaller coverage areas, hence requiring more and ultra-dense base-station deployments with tiny cells, are evident challenges related to using the THz band. Additional challenges of using the THz band in 6G are summarized in table III. THz wireless communication needs small antenna sizes in order to achieve diversity gain [2]. This requires ultra-Massive MIMO to facilitate THz wireless communication in 6G networks. In this regard, Large Intelligent Surfaces (LIS) can be used with 6G to go beyond massive MIMO to facilitate THz range frequencies. The directionality feature of the THz band also raises serious issues for medium and random access protocols. Non-orthogonal multiple access (NOMA) and beamforming are promising solutions to combat highly directional transmissions of THz signals. In particular, NOMA allows multiple users to share the same THz beam, thus enabling massive IoT connectivity [12]. Other major challenges of THz communication include channel modeling, resource optimization, and health issues.

IV. Artificial Intelligence

Researchers are considering the vision, essential enabling technologies, and use cases for 6G as the worldwide rollout of 5G continues. The deployment, design, and operating phases of the 6G layers depicted in Table I are expected to be made possible by AI [13]–[15]. AI will evolve the conventional methods to a flexible and programmable-based network that would help optimize the network management process in 6G [16]. Furthermore, the intelligent agents using AI methods will help solve complex problems on vast scales that could result in the provision of concurrent connections and new sensing technologies [17]. In fact, with the inclusion of AI, 6G systems would become *cognitive* in a legitimate way. For instance, communication aspects of 6G, including spectrum sharing, radio resource management, quality of service, network slicing, and virtualization, will hinge on AI techniques to solve intricate and domain-specific problems.

A. Application of 6G Technology and AI

With 6G technology, AI will play a key role in reshaping communication-based services, as well as the other applications addressed in Table II. For example, self-driving cars in the auto industry need to know about their constantly changing environment, location, pedestrians, cyclists, and other cars in order to find the best route and get through intersections. Handling, generating, and processing large amounts of data simultaneously in collaboration is another task that needs AI (intelligent agents) to solve complex problems in real time on a larger scale. Moreover, it can be used in all emerging industries, not merely the auto industry.

In the field of artificial intelligence, potential future applications of 6G technology include the more traditional uses, which include diagnostic, prescriptive, and descriptive analytics [18]. Prescriptive analytics can be used to make judgments or make predictions relating to edge computing, cache placement, network virtualization, slicing, resource allocation, and other related topics [19]. With the use of predictive analytics, one may make educated guesses about the future based on the data that has been collected in real time and applied to factors such as the availability of resources, preferences, user behavior, user locations, and traffic patterns. The purpose of diagnostic analytics is to identify problems inside a network, which includes locating network abnormalities, service impairments, network failures, and their underlying causes. This, in turn, contributes to an improvement in the network's level of dependability and security. In order to improve the service provider's and network operator's situational awareness, descriptive analytics largely rely on previous data. The apps cover a wide range of topics, such as user views, channel conditions, traffic profiles, and network performance, among others.

B. Challenges in AI Deployment and Potential Solutions

When the aforementioned use cases and applications discussed in preceding sections are taken into consideration, it is reasonable to think that AI can be incorporated into 6G systems on both fronts, i.e. components and applications, in the appropriate manner [18]. Despite this, these enabling 6G components are just in their first phases and still need to solve a number of difficulties, which are outlined in the table referenced (c.f. Table III). For instance, it is obvious that the use of AI in 6G needs the mining of massive amounts of data, which presents questions about the ownership of data, as well as ethics, privacy, and security, among other issues. In addition, Unmanned Aerial Vehicles (UAVs) can also become a part of the edge computing infrastructure of 6G networks to facilitate AI processing in 6G networks [20]. In addition, rules and laws need to be drafted in order to preserve data integrity, privacy, and security during the process of building the network architectures and protocols in the context of 6G in order to achieve an appropriate balance between the potential benefits and potential dangers. In addition, the difficulties become more varied when dealing with distinct sets of applications, such as healthcare optimization, financial market monitoring, smart grids, extended reality, and industry 5.0 [15].

V. Distributed Ledger Technology and Blockchain

DLT is touted to have a broader scope to contribute towards the growth of 6G networks and its applications. DLT enables secure and distributed storage of a digital ledger at all the participating nodes in the underlying network using the same protocol [21]. Thus, all the nodes independently maintain an identical copy of the digital ledger. One of the prominent types of DLT is BC which has received all-around attention [21]. BC follows a specific structure to create and update the distributed ledger. It comprises immutable blocks (containing set of valid transactions) that are timestamped and are connected using a hash-based chain. In other words, in BC, transactions are validated, clubbed together, and cryptographically sealed in a unit called a block. The newly created block is appended to the BC by connecting it with the last block in the ledger using a cryptographic hash-based chain. This chaining is indeed established by inserting the hash of the previous block in (the header of) the newly created block. Some of the well-know characteristics of BC are immutability, non-repudiation, provenance, enhanced security, pseudonymity, distributed database, and decentralized operations.

A. 6G Applicability

DLT, and in particular BC technology, has the capability to address many prevailing issues related to 6G development, such as, flexibility, autonomous and intelligent operation, security, privacy, accountability, interoperability, and efficient resource management. However, this requires the integration of DLT/blockchain with 6G networks. For instance, BC can be instrumental in terms of efficient spectrum sharing in 6G wireless networks. BC, along with smart contracts, can reduce the administrative costs and issues pertaining to the centralized management of spectrum [8] and resource sharing [22]. BC with smart contracts also has the potential to establish dynamic agreements and effectuate seamless roaming instances and

TABLE II: Applicability of the technological directions for 6G applications

Technology Direction	6G Application: Industry 5.0	Intelligent Healthcare	Internet of Everything	Smart Grid 2.0	UAV/Connected Autonomous Vehicles	XR/Holographic Telepresence
Intent-based Networking	Eliminate manual configurations, improved system agility, fast network services deployment	Fast network services deployment, improved security and privacy, reduced complexity	Fast network services deployment, improved security and privacy, reduced complexity	Eliminate manual configurations, improved security and privacy, reduced complexity	Improved security and privacy, reduced complexity, fast network services deployment	Fast network services deployment, improved security and privacy
THz Communication	Improved wireless security and control	THz imaging/sensing in smart healthcare, THz nano-/in-body communication	THz tiny-cell for provide seamless connectivity to everything	Gbps communication for efficient pricing control and transmissions among end devices	Ultra-fast and dense aerial access networks	Tbps transmissions between end devices and edge computing servers
Artificial Intelligence	Autonomous tasking for cobots, neural links for controlling machines remotely	Automatic analysis of health records, real-time monitoring and recommendations	Heterogeneous data analysis, condition based recommendations, intelligent services	Intelligent load allocation and balancing, rerouting in case of disasters	Energy efficiency routing protocols, rerouting, computational offloading, shortest path finding	Advanced computer vision techniques to recognize environment and gestures
DLT and Blockchain	Enhanced security, privacy protection, dynamic business contracts	Secure patient monitoring, automated handling of medical insurance	Decentralized computation, distributed storage, secure communication, smart contracts	decentralized automated smart grids, open market energy trading	Identity management, fault tolerance, decentralized security management	Decentralized content market places, security and privacy protection
Smart Devices and Gadgets	Digital twin operation, cobots, automated industries, supply chain management	Tele-surgery, teleconsultation, smart-wearables	Advanced sensors with efficient operation and communication	Smart energy meters, sensors, renewable energy generators	Advanced drones, smart vehicles, autonomous vehicles	XR devices, haptics, holographic displays, gadget-free communication
Quantum Communication	Scalable quantum routing for fast data transport	Enable quantum teleportation in robotic surgery	Quantum key distribution in IoE to enable security features	Intelligent control systems, secure communication between nodes	Multi-degree of Freedom, high purity for Internet of Vehicles	Multipartite entanglements of purification and holography

tackle roaming frauds [23]. Furthermore, BC can enhance the applicability of AI/ML techniques for 6G networks and applications by providing enhanced security and privacy-protection [7], [24]. Furthermore, BC can ensure the overall security of 6G networks at different layers as depicted in table I. Another directions where BC can play a significant role is to support the new range of 6G applications are presented in table II). DLT/BC, with its underlying cryptographic mechanisms, distributed database, consensus protocols, and smart contracts, can satisfy the crucial requirements of these applications such as secure and privacy-protected data exchange, strict access control, traceability, and identity verification [2], [25]. Furthermore, DLT/BC is instrumental in establishing an open market and business model of 6G [26]. Thanks to the intrinsic capabilities of DLT/BC, different network operators, third-party vendors, and resource providers can participate in building complex 6G ecosystems in a trustless yet auditable manner. For instance, European Telecommunications Standards Institute (ETSI) has initiated Industry Specification Group on Permissioned Distributed Ledger (ISG PDL) to explore the applicability of permissioned distributed ledger for developing an industrial open ecosystem [27].

B. Deployment Challenges and Possible Solutions

The integration of blockchain with 6G demands several challenges to be addressed. For instance, with the proliferation of connected IoE devices, data-intensive new applications, and high-speed communication infrastructure, a large number of transactions will be pushed to DLT based 6G system. Accordingly, the system will require a very high throughput, i.e., the ability to process a large number of transactions per unit of time. The verified transactions need to be stored at all the nodes independently, which will blow up the storage capacity. Moreover, the bigger the database (ledger), the higher the time required to verify a new transaction, which will increase the latency. Though DLT/BC can enable transactions between untrusted stakeholders, it is prone to security attacks like DDoS attacks or AI-related attacks. Some possible solutions are sharding or hierarchical BC for throughput, off-chain storage or sidechain for storage, homomorphic signature, and Trusted Execution Environment (TEE) for security, and Privacy Enhancing Technologies (PETs) and Attribute-Based Encryption (ABE) for privacy. Furthermore, enhancing the interoperability to facilitate seamsless operation of networks, limited data replication among nodes to increase the scalability, developing more energy and time efficient consensus algorithms, and developing standards for blockchain developments needs to be overcome in order to realize a tighter integration between blockchain and emerging 6G networks.

VI. Smart Devices and Gadget-free Communication

Over 24 billion smart devices, including smartphones, smart sensors, smart wearables, and smart machinery, are expected to be connected to 6G networks by 2030 [2]. These devices will pack advanced technologies, smart screens and sensors to provide personalized digital services banking on the edge-intelligence capabilities of future networks. Furthermore, user interfaces will harness technologies such as Extended Reality (XR) and Holographic Telepresence (HT) to enable a plethora of smart services such as intelligent health-care, smart cities and Industry 5.0 [2]. Gadget-free communication is another area that is expected to disrupt the way people access digital services [28]. Gadget-free communication will eliminate physical devices while providing an *omnipotential* user environment through holograms, haptics and digital interfaces.

TABLE III: Technological developments, potential, challenges and solutions of the six disruptive technologies towards 6G

Technological Development	Potential as an Enabling Technology	Existing Challenges	Possible Solutions
Intent-based Networking			
IBN Controller	Automatic intent translation and conflict resolution, optimization of network layout, configuration, and activation strategy	Optimal deployment of the IBN controller and enabling data processing in 6G Core Network (CN) and RAN	Hybrid IBN controllers in centralized cloud and edge, distributed data collection, processing and resource optimization
Intent-driven Wireless Networks	Intelligent and automatic intent translation into network configuration	Issues related to data collection, data types, model training, algorithm selection	AI model training infrastructure at the appropriate network segments, efficient model training and resource allocation
THz Communication			
New Channel Models	Model THz communication in indoor applications or outdoor scenarios with ideal conditions	Accurate channel model for all THz communication scenarios not possible due to very high absorption loss	Tiny cells deployment to address short communication distance, efficient resource and interference management schemes
Advanced Transceiver/antenna Designs	Transceiver and antenna design plays key role to enable THz communication	Cost and power consumption of dedicated RF components for individual antennas, deployment of THz antennas	Hybrid beamforming solutions, high-gain and fast-tracking antennas using nano materials
New MAC and networking Protocols	Settle antenna directionality challenges, enhance network performance via efficient medium access schemes, THz line-of-sight link selection	Issues in MAC and networking protocols (interference management, adaptive beamforming, line-of-sight blockage, deafness)	Cross-layer MAC protocols to consider user scheduling at the medium access layer and path selection at the network layer
Artificial Intelligence			
Data Sensing	Process data acquired from millions of devices	Large amounts of data processing can overload the system, Continuous data transmission decreases power efficiency	Use of AI at the sensor site for local analysis or summarization to achieve better energy efficiency
Spectrum sensing	Cognitive radios, spectrum sensing assist users join network irrespective of their primary affiliation	Primary users may get affected, power consumption might increase due to continuous scanning of available spectrum	Co-operative Spectrum Sensing that uses AI technology can be used for efficient utilization of frequency spectrum
Data Heterogeneity	Connect devices varying in terms of sample rate, scientific metric, data type	Difficulty in data analysis due to varying data types	AI allows data to be transformed in latent/feature space for data analysis
DLT/BC			
Smart Contracts	Softwarization of the clauses of agreement, self-execution when predefined conditions are reached, strict access control to data	No legal framework, difficult to understand coded agreements, various kind of attacks (DAO, Parity Multi-Sig Wallet, rubix)	Establish legal frameworks, develop and use security and privacy preserving tools, Formal methods to analyze vulnerabilities
Cryptographic Techniques	Protect network resources and spectrum, enhanced security and privacy	Secure key management using lightweight protocol with minimum overheads, system collapses if private key is captured	Quantum Key Distribution (QKD) for key management, homomorphic and Attributed Based Encryption (ABE) to protect privacy
Consensus Mechanisms	Allow decentralized 6G ecosystem, offer fault tolerance	High convergence time, lightweight smart consensus algorithm design with high fault tolerance	Smart consensus algorithm design using environmental parameters, create quantum-safe consensus mechanisms
Smart Devices and Gadgets			
Further enhanced Mobile Broadband (FeMBB) and Mobile Broad-Band and Low-Latency (MB-BLL)	Provide high data rates, high reliability and ultra low latency network connectivity	Bandwidth limitations, poor network reliability and availability	More bandwidth, VLC for low latency communication, QC for ultra reliable communication
Holographic Displays and Projectors	Enable holographic communication, gadget-free communication through holograms, virtual tele-presence	Accurate representation of information, gesture recognition, real-time processing of large amounts of data	Light-field 3-D displays, 3-D touch-sensing, edge intelligence for real-time data processing
Edge Intelligence	Provide smart devices with real-time access to powerful computational resources	Network latency, data scarcity, data consistency, incentive mechanisms, data security and privacy	THz spectrum for better connectivity, AI/swarm intelligence, DLT/BC for decentralized resource management
Quantum Communication			
Quantum enabled Communication	Potential to exploit laws of physics, i.e., photon states, to make communication faster	Long-distance transmission of quantum states	Polarization preserving quantum frequency between atom and telecom photon to communicate over 20km through fiber
Quantum enabled IoT	Integration of computational components incorporating quantum computers with neuromorphic chips for fast computation	How to monitor and ensure quality services from all devices	Quantum-Temporal Minimization Algorithm to enhance temporal effectiveness, performance, and quality of service
Quantum enabled Security	Quantum cryptography exploits the quantum theory and its mechanism to enhance secure end-to-end communications.	Important challenges such as distance, secret key rate, size, and practical security.	Long distance QKD over fiber. In addition, QKD extends the resulting of higher secret key rates in wide area networks

User interactions will be detected through multiple sensors capable of capturing user inputs such as voice, and gestures.

A. 6G Applicability

Smart devices and Gadget free communication is envisaged to be a key technology direction towards 6G, as highlighted in table I. SDG plays a key role in enabling futuristic 6G applications as presented in table II. For instance, in Industry 5.0 applications, various cyber-physical systems are expected to facilitate autonomous manufacturing in smart factory environments. These systems can be operated, monitored and maintained through their digital-twin banking on technologies such as XR and holographic communication. Furthermore, healthcare applications connecting heterogeneous Intelligent Internet of Medical Things (IIoMT) devices generate large volumes of *Big Data* that needs to be processed using AI/ML to facilitate advanced healthcare services. Hospital visits can also be minimized using gadget free communication to create a virtual presence of medical professionals for patients. In addition, CAVs will self-charge, self-diagnose and self-maintain connecting to the envisaged Energy Internet (EI) and edge intelligence based services. UAVs are also expected to be used in many areas including industrial, commercial, communication, military and cinema environments. These UAVs will be controlled using edge intelligence and Brain Computer Interfaces (BCI) integrated with future 6G networks.

B. Deployment Challenges and Possible Solutions

SDG will burgeon owing to the advancements of electronics, computing, smart screens, and more importantly, the envisaged features through future 6G communication networks, such as, extremely high data rates, extremely low latency, extremely high reliability and availability, and edge intelligence [2]. The SDG technological developments, challenges and solutions towards 6G are tabulated in table III. Accordingly, multi-core processors with advanced power management techniques enable smart devices to drive multiple sensors and high definition screens. Moreover, research and development work are progressing towards realizing 360-degree transparent holographic screen displays. In addition, the network requirements to facilitate SDG communication are expected to be realized through developments in technologies such as THz spectrum, Visible Light Communication (VLC), and Large Intelligent Surfaces (LIS). Also, connecting an extremely large number of smart devices, sensors and gadgets in a decentralized manner to future 6G networks is expected to be a significant challenge that is envisaged to be realized through DLT/BC and zero touch network and service management technologies. In addition, edge intelligence capabilities in future 6G networks can be harnessed to process large amounts of data obtained through many devices in real-time to provide advanced digital services. Furthermore, efficient mechanisms are investigated to ensure network security and user privacy in future 6G networks with SDG.

VII. Quantum Communication

Quantum computing enabled communications has derived a lot of research and development interests recently. Slowly but beyond mere science fiction, QC will be a transformative reality in the 6G paradigm in the next decade or so [29]. As 6G must meet stringent requirement, such as massive data rates, fast computing, and strong security, QC will be a potential enabler. The driving force of QC is that it exploits traditional concepts of physics i.e., photons are being used to process the computation to the quantum qubits [30]. These qubits are then sent from a sender (or emitter) machine to a receiver machine. Using flying qubits in communications brings enormous advantages, such as, weak interaction with an environment, faster computations and communications, quantum teleportation, communication security, and low transmission losses in communication [31]. These exciting features will make QC one of key enabling technologies in 6G.

A. 6G Applicability

Researchers have been considering and developing QC-enabled 6G use-cases that will reshape the future of communication. For instance, quantum optical network will complement to achieve almost unlimited capacity of 6G mobile broadband services. However, this would require advanced algorithms or methods, such as advanced signal processing, that is capable of performing the direct transformation of information between THz and optical domains. Quantum technologies (e.g., based on plasmonics modulators) would be an enabler in this research direction [30]. One earliest work (i.e., [32]) proposed an ultra-broadband plasmonic modulator that exploits the applications of quantum-based technologies in communication systems and networks. 6G research has ignited more innovative techniques (e.g., quantum access network framework, quantum switching, and QC-enabled AI) and will continue to develop to realize QC-enabled 6G services. For instance, in [33] Granelli et al. proposed a new architecture that would enable future classical-quantum communication for future networks. The architecture employs the idea of softwarization (through software define network, and network function virtualization). It combines mainly 4G and 5G enabled mobile-broadband/Internet, and three- dimensional (i.e., data, control and quantum capabilities) of 6G communication networks via quantum physical layer. The main benefits of this architecture would be the representation of quantum and legacy Internet as a single controlled and independent-integrated entity. Equally, QC will facilitate the communication requirements of IoE where millions of devices will be employed to collect data and demand reliable, unreliable, and low-cost communication technologies. However, designing, developing, and standardizing new security architectures, encryption standards, and data security mechanisms for quantum computing is yet to be progressed [34].

B. Deployment Challenges and Possible Solutions

Realization of QC for 6G applications imposes significant challenges in predicting QC solutions, services and applications. One fundamental challenge is long-distance transmission of the quantum states. However, the states of quantum qubits can play a paramount role due to their robustness to noise and capacity to carry information is high. The implementation of quantum states is not easy due to many reasons including limited resources, and lack of enough practical knowledge. Some theoretical areas are also yet to be properly explored. Another challenge is optical quantum memory storage. Many researches have already proved the capacity to store multidimensional states in quantum memories is possible. However, very few researchers have shown the adaptability within the external qubit sources and high-dimensional states stored in quantum memories. In addition, the data accuracy will be challenging in 6G enabled IoE. Recent innovations of quantum computing-inspired optimization (QCiO) have provided new paths for achieving data accuracy for real-world applications. In [35], the authors presented an QCiO to acquire IoT sensor data in the quantum form and achieved high data accuracy and data temporal efficiency. Yet another interesting challenges of quantum-based security solutions (e.g., QKD) are whether they are viable to resource-constrained IoE devices. However, QKD has its own challenges such as secret key rate (few Mbps), distance (few 100s Km), and practical and formal security verification. Therefore, new insights are needed to be explored on quantum-based security solutions and their viability in resource-constrained environments.

VIII. Conclusion

This paper focuses on six technological directions towards realizing 6G, the next generation of mobile networks. These technological directions are IBN, THz communication, AI, DLT/BC, smart devices and gadget-free communication, and quantum communication. It is evident that that the six technological directions elaborated in this paper are expected to play a major role towards the realization of 6G. The paper presents technological developments, 6G applicability, existing challenges and possible solutions under each technology direction. Accordingly, the proposed solutions can be explored towards overcoming some of the existing challenges towards developing 6G mobile networks. It is also envisaged that the paper will pave the path to focus future research and development work towards the six technological directions discussed in this paper to realize 6G in the coming decade.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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