A Speculative Study on 6G

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***Abstract*—While 5G is being tested worldwide and anticipated to be rolled out gradually in 2019, researchers around the world are beginning to turn their attention to what 6G might be in 10+ years time, and there are already initiatives in various countries focusing on the research of possible 6G technologies. This article aims to extend the vision of 5G to more ambitious scenarios in a more distant future and speculates on the visionary technologies that could provide the step changes needed for enabling 6G.**

***Index Terms*—B5G, Emerging technologies, 6G.**

I. Introduction

The last decade has experienced a never-ending growth in the global mobile data traffic. The International Telecommunication Union (ITU) predicted that the overall mobile data traffic will reach 5 zettabytes (ZB) per month, see Fig. 1. The fifth generation (5G) is the latest attempt that brings mobile communications technology up to speed but it is expected that 5G will reach its limits by 2030 and the chase continues.

Coupled with the rises of Internet-of-Things (IoT), massive machine-type communications (MTC) and etc, 5G is so much more than traditional cellular networks. European Telecommunications Standards Institute (ETSI) published a document on 5G scenarios where the target peak rate is 10Gbps in the uplink and 20Gbps for the downlink (3GPP TR 38.913).

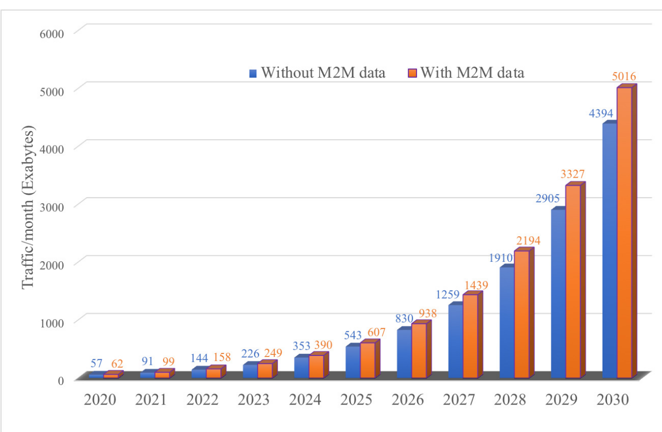

Fig. 1. Global mobile data traffic forecast by ITU. Overall mobile data traffic is estimated to grow at an annual rate of around 55% in 2020–2030 to reach 607 exabytes (EB) in 2025 and 5,016 EB in 2030. (Source: Cisco)

The myriad of emerging massively data-intensive use cases such as multi-way virtual meeting with holographic projection [1], virtual and augmented reality (VAR) [2], brain communication interface [3], even teleportation [4], remote surgery and etc. [5], to name just a few, indicates that the latency, reliability and data rate requirements of future applications are clearly beyond the capacity of the 5G systems being launched. Thus the next step change in 6G will need to be called upon to fully support the services. Presumably, 6G will continue to benefit from many 5G technologies, but new technologies will certainly be needed to make the next step change.

The objective of this article is to provide an expert view on the most trending and novel research directions that have the potential to shape the 6G mobile technologies. Although the development of 6G is in an early stage and it is expected that some ideas will only emerge in later years, this visionary article takes a bravery approach to speculate on the possible enabling technologies and the revolutionary elements in 6G, and describe their features beyond the capability of 5G.

The rest of this article is organized as follows. In Section II, we present our 6G vision and speculate on the requirements. Section III then extends some 5G use cases to more ambitious scenarios that are expected to appear in 6G. We will discuss some key challenges in Section V, and present a few visionary technologies or research directions that may form key parts of 6G. Finally, we conclude this article in Section VI.

II. Vision

Building upon the 5G vision, 6G will continue to empower our cities with exceptional intelligence and full connectivity with a plethora of autonomous services. We will experience widespread proliferation of humanoid robotic and intelligent devices capable of decision making with minimum human intervention. This will result in demise or significant reduction of traditional mobile/handheld devices. Everything around us will be very intelligent, giving rise to the concept of Internet of Intelligent Things (IoIT) underpinned by artificial intelligence (AI) capability embedded in almost all levels, from network orchestration and management to coding and signal processing, manipulation of smart structures, and data mining for service-based context-aware communications. Few will disagree that AI will be an integral part of 6G due to the availability of big data and advances in computation capability.

Recent interest has also shifted towards virtulization and softwarization of physical resources and infrastructure which will ensure intelligent organization of contents and make them available at the network edge resulting in orders of magnitude improvements in terms of latency and energy efficiency.

Our 6G vision is driven by several revolutionary changes that will see 6G leap beyond the capability of 5G. We discuss these ideas below and elaborate them in Section IV.

In 6G, we anticipate to see AI in operation with distributed training at the network edges including small-cell base stations (SBS) and user equipments (UEs). In contrast to the use of conventional AI algorithms on mobile network data as in 5G, 6G will look to realize the notion of *collective AI*, a step-up from the current AI techniques that will address the coexistence of multiple distributed mobile radio learning agents for individual as well as *global* benefits. This step change may be realized by an integration between reinforcement leaning and game theory. To accommodate such intense computation for AI, devices will also experience a paradigm shift in terms of design, operation, size and chip architecture. Next generation of neuromorphic chips capable of emulating complex brain function will emerge, benefiting from the advances in nano-photonics and nanoscale laser technologies to deliver billion times faster computation than biological neurons.

At the device level, another reality is that (nano) radar technologies will be integrated with mobile communication technologies in order to provide all-round contextual information. 6G will likely see physical-layer security finally thrive to provide a new layer of defence, in addition to cryptographic techniques, for devices with different constraints and capabilities. Devices will also be much smarter, interpreting the behavioural data of the environment from radars using AI.

On the other hand, after 30 years of effort, 6G will finally see Mitola radio, a.k.a. cognitive radio, reach its full potential. Despite the enormous interest after Mitola *et al.* first introduced the concept back in 1999 [6], little has been achieved so far and there is still a huge gap between 5G new radio (NR) and the cognitive radio Mitola envisioned. The 6G Mitola radio will see self-regulating societies of mobile radios for fair as well as efficient coexistence and facilitate seamless mobile convergence across all wireless systems and networks.

Apart from these, there will be a paradigm shift in developing wireless communication technologies. Instead of attempting to develop generalized and robust techniques that work for arbitrary wireless environments and conditions, the focus will be shifted to developing an intelligent wireless communication environment as a closed loop, by using software-controllable metasurfaces and pervasive AI intelligence. Smart reflective surfaces will be installed in buildings, and indoor environments to enlarge the antenna aperture to collect as much radio signals as possible, and adapt the environment best suited to the wireless applications. Such smart structures seek to engineer the environment to cater different applications, to improve link quality, block interference, enhance privacy and security, avoid adversarial attacks and many more [2], [4].

Software-controlled materials are not limited to the large scale. In the smaller scale, 6G will also see flexible antenna structure possible at the UEs. Early results on fluid antennas in [7], [8] give hope to a whole new possibility for designing mechanically flexible antennas for ultimate reconfigurability and adaptation for wireless communications systems. The prospect of software-controlled mechanically flexible antennas will see UEs unlock the space limitation for extraordinary diversity and multiplexing gains. Combining with metamaterial-based antenna designs for compactness, 6G will have a totally new version of multiple antenna technologies at the UEs.

There is also glimpse of successes in other emerging areas which are not yet making much of an impact in 5G but could become reality in 6G, including wireless power transfer (WPT) and RF energy harvesting for massively distributed battery-less nano-sensors, optical wireless communications or Li-Fi. Furthermore, there is a possibility that 6G will be more than wireless, and need to handle coexistence of traditional mobile communications and interconnects inside PCs. Fig. 2 provides a snapshot of what 6G may embrace.

Characteristics	**5G**	**6G**
Individual data rate	1 Gbps	100 Gbps
DL data rate	20 Gbps	> 1 Tbps
U-plane latency	0.5 ms	< 0.1 ms
C-plane latency	10 ms	< 1 ms
Mobility	up to 500 km/h	up to 1000 km/hr
DL spectral efficiency	30 bps/Hz	100 bps/Hz
Operating frequency	$3 - 300$ GHz	up to 1 THz

TABLE I
KPIs FOR 5G VERSUS 6G.

In terms of the requirements in 6G, the consensus seems to be that the data rate will race to 1Tbps to enable autonomous management of various activities in future smart cities. This target data rate primarily suits the spectrum availability which is also anticipated to move towards the terahartz band capable of delivering Tbps. For each UE, the data rate will increase from 1Gbps in 5G to at least 10Gbps and up to 100Gbps in some use cases (such as holographic projection where for super high vision 10K videos with 60fps and 16-bit colour depth, it will need around 160Gbps data rate), in the emerging 6G systems. For backhaul, the rate will rise to 10Tbps to ensure support for high data rate applications such as VAR [1]. 6G is also expected to integrate with satellites for providing global mobile coverage. Volume spectral efficiency (in bps/Hz/m^3), as opposed to the often used area spectral efficiency (bps/Hz/m^2), will be more suitable in 6G to properly measure the system capacity in a three dimensional operating space. Ultra-reliable low-latency communication (URLLC), one key feature in 5G NR, will be a key driver in 6G again requiring latency of less than 1ms in C plane and 0.1ms in U plane. Application such as remote surgery cannot be realized if the latency is not below these values and will pose significant risk to the patient. Energy efficiency will be extremely important to prolong the battery life of UEs. The key performance indicators (KPIs) for 6G in comparison with 5G are summarized in Table I.

III. USE CASES

Most of the use cases in 6G will evolve from those of 5G in terms of functionalities and quality of experience. As 5G use cases are being designed to overcome the communication distance barriers, 6G use cases may be viewed as overcoming the limitations of physical distance barriers. Here, we use some examples to describe what 6G may bring beyond 5G. A comparison of their use cases is provided in Table II.

A. Immersive eXtended Reality (IXR)

As significant focus of 6G technologies will aim towards overcoming the operational barriers created by physical distance, IXR enabled by haptic communication, advanced VAR, holographic projection, and etc. will be a dominant use case.

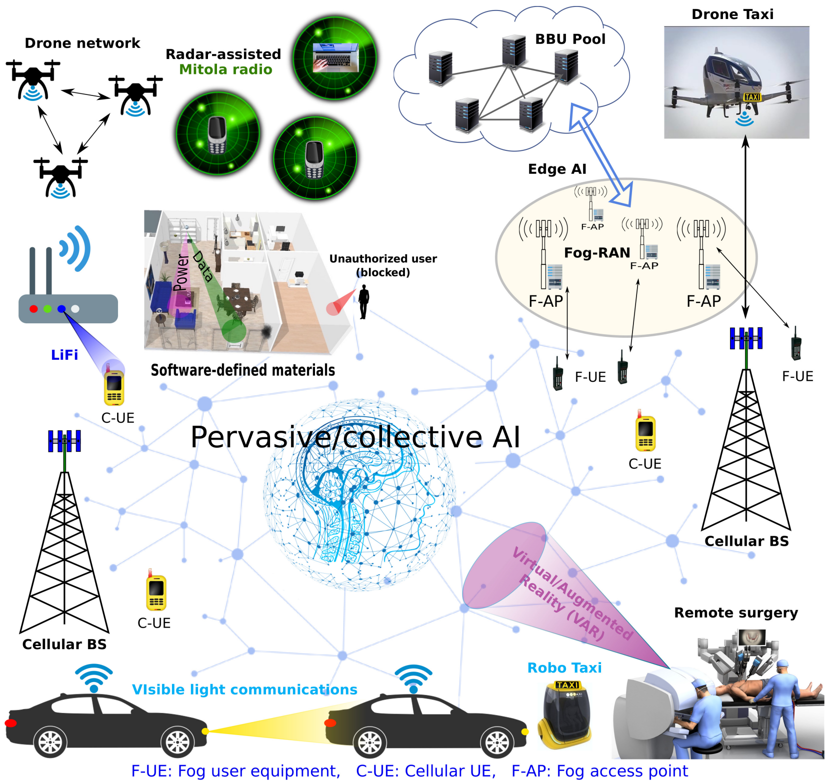

Fig. 2. The vision of 6G.

Use case	5G	6G
Centre of gravity	user-centric	service-centric
Ultra-sensitive applications	not feasible	feasible
True AI	absent	present
Reliability	not extreme	extreme
VAR	partial	massive scale
Time buffer	not real-time	real-time
Capacity	1-D (bps/Hz) or 2-D (bps/Hz/m^2)	3-D (bps/Hz/m^3)
VLC	no	yes
Satellite integration	no	yes
WPT	no	yes
Smart city components	separate	integrated
Autonomous V2X	partially	fully

TABLE II
COMPARISON BETWEEN 5G AND 6G USE CASES.

The hangout and meetings that are happening via video calls will be shifted towards a holographic presence giving a more realistic feel. Surgeons will carry out sophisticated surgery in distant hospitals while engineers will be able to solve mechanical problems from remote locations with the aid of extended reality environment. Distance learning and education will thrive as people will learn from using VAR technologies. Biological research and experiments which took decades will be completed in years or even months by realistic simulations created in IXR coupled with advanced AI capabilities.

These use cases are all data intensive and will require 100s of Gbps data rate. However, 5G is not designed to support ubiquitous holographic projections from multiple locations in bidirectional communication that requires terabit data transfer. Also, multi-view video coding will need to advance greatly to achieve extreme data compression. Apart from these, bidirectional and closed loop latency requirement of at least 10 times quicker (0.1ms) than current capabilities are required for applications such as remote surgery. While 5G can provide some basic mixed reality support in very controlled environments, they are simply not capable of supporting these applications in uncontrolled environments such as outdoor scenarios.

B. *IoIT Integrated Ultra Smart City-Life*

The jargon 'smart city' describes the concept where a city greatly improves the quality of life (QoL) for the people in it by optimizing its operations and functions using the available infrastructures to sense, detect, analyze and act by integrating the core components that run the city. Nevertheless, in 5G, a city can only be fragmentally smart, meaning that the major components such as utilities (i.e., electricity, water and waste, etc.), healthcare and monitoring, and transportation networks are individually smart. 6G will take a holistic approach in an integrated fashion for a truly smart city. Some example use cases of the future city-life are elaborated below.

1) Super Smart Home Environment: Most elements around us will have brain, benefiting from the rapid development in neuromorphic chip design as well as advances in pervasive AI. There will be data fusion from myriads of (nano) sensors embedded in all the elements. The IoIT infrastructure will be predominantly be operated by voice, gestures and other types of sensory communications. Thus, complete rethinking in the system design approach to cater such enormous wireless connectivity, integrated with the environment, will be necessary.

2) Ultra Smart Transport Infrastructure: The automotive and transportation industries are experiencing a generation change, partly due to the connectivity and networking capability offered by 5G and beyond systems. With the emergence of 6G, the overall transportation system will be influenced by three things. First, the in-vehicle sensors and actuators will be intelligent, enabled by brain-like AI for fully autonomous vehicles. Secondly, overcoming physical barriers require reducing lots of travelling and where people do travel, they will be taken by autonomous vehicles. Third, with the aid of AI and extreme data rate capability, safety and security will be ensured by massively embedded intelligent sensors and actuators. Note that massive amount of data will need to be shared amongst vehicles to update live traffic and real-time hazard information on the roads and provide real-time high-definition 3D maps. As vehicles generally move at very high speeds, the network needs extremely low round-trip time for communication. It is likely that vehicle-to-everything (V2X) technologies will not mature in 5G and its full potential will only be realized in 6G with visible light communication (VLC), orbital angular momentum (OAM) and emerging terahertz technologies.

3) Smart Ubiquitous Healthcare: Ageing population is putting a huge burden on healthcare systems worldwide. Rapid developments in bendable electronics and nano-biosensors will revolutionize health monitoring and management. In 5G, some of the technologies are expected to be available in a localized fashion. Nevertheless, ubiquitous high quality coverage of 6G will enable remote healthcare management aimed at providing round the clock care regardless of the location of the patients. However, extreme latency and reliability will be key to ensure that emergency procedures and interventions are done in timely and uninterrupted manner. Also, progress in soft and medical robotics coupled with IXR will provide remote surgery and intervention from distance. Therefore, surgeons with certain expertise can assist and supervise robots to carry out procedures from anywhere around the world provided that the critical latency and safety requirements are met. Privacy is another concern which will be addressed by blockchain or variants of distributed ledger technology, all happening under the ultimate connectivity and supreme quality of 6G.

C. Industry X.0

Massive incorporation of robots into automation and warehouse transportation is vital for industry growth. The emerging concept of Industry X.0 aims to enhance the Industry 4.0 by exploiting social, mobile, analytics and cloud (SMAC). The radio environment with a very complex network comprised of hundreds or thousands of robots, sensors and hardware elements is a challenge. 6G will fully support the Industry X.0 revolution by offering extreme latency and reliability as well as massive IoT and built-in AI capability.

IV. Key Enabling Technologies

6G will look for another major leap from 5G, which would only be possible if breakthroughs could be achieved. Here we share some emerging ideas that could contribute significantly to enable 6G in the next 10 years or so. Table III provides a handy comparison of various 6G approaches in the literature on key enablers, use cases and associated KPIs.

A. Pervasive AI

Without a doubt, AI will be at the core of 6G (cf. Fig. 2). Due to the advances in AI techniques especially deep learning and the availability of massive training data, recent years have seen an overwhelming interest in using AI for the design and optimization of wireless networks. AI is expected to play a key role in all areas. Those can be broadly classified in three levels namely, the end UE, localized network domain level and overall network level. This will transform the 6G network from self organizing to the self sustaining regime [3].

Deep learning, the most powerful AI techniques at present, is however based on deep neural network (DNN), which relies on training in a centralized fashion. Yet 6G is moving towards a more distributed architecture handling millions and billions of end-to-end communications anywhere around the world. The distributed cloud structure necessitates training to be done at the network edges and handicaps the operation of deep learning. Although the recently developed federated learning partly addresses this problem by allowing training to take place at distributed locations, this is more a distributed implementation for centralized learning, and communications between the distributed clouds and a central network manager is required. Also, federated learning for optimization is much less powerful because updates in the user level are averaged before sending back to the central manager.

For 6G to succeed, AI needs to be integrated with game theory to enable a truly distributed learning mechanism where many AI agents can teach and learn from each other by interactions. Collective AI is a related concept that has emerged recently to deal with the situation where multiple AI agents aim to achieve the same goal based on local teaching and learning with no direct communication amongst the agents [9]. Moreover, over the next decade, we will see that devices become capable of reprogramming themselves and allow them to reconfigure their functionalities as required, which is also enabled by AI-controlled flexible materials. We predict that future software-hardware co-development will transform collective and pervasive AI into brain-like functioning elements, thereby providing the true brain power to 6G.

B. Radar-Enabled Contextual Communications

Radar technologies enrich environmental awareness for mobile UEs and IoT devices and enable context-aware communications to the level that has not been possible before. In particular, recent development in millimeter-wave (mmWave) radars allows them to be embedded in mobile devices and since the miniaturisation will continue, more of them can be embedded in a single device. This will give 6G radios the environmental awareness to empower AI at the device level. Combining the rich observations from radars with AI, UEs will be able to identify and localize potential adversaries by observations from radars and adapt their communications for enhanced protection using physical layer security approaches. 6G Mitola radios will also store and exploit behavioural data of

Attribute \ Paper	Yang *et al.* [5]	Zhang *et al.* [1]	Saad *et al.* [3]	Giordani *et al.* [4]	Strinati *et al.* [2]	This article
Peak data rate	1 Tbps	1 Tbps	1 Tbps	5 Tbps (for VAR)	1 Tbps	1 Tbps
Backhaul rate	X	10 Tbps	X	X	X	10 Tbps
Volumetric capacity	X	X	✓	X	1-10 Gbps/m^3	✓
Operating frequency	0.06 to 10THz	Up to 10THZ	300GHz + Visible Light frequency (VLF)	100GHz to 10THz + VLF	Sub THz band + VLF	Up to 1 THz + VLF
Mobility	X	$\geq$ 1000km/h	X	1000 km/h	X	1000 km/h
Latency	$\leq$ 1ms	0.01-0.1ms	$\leq$ 1ms	$\leq$1ms	1ms	Cplane: $\leq$ 1ms Uplane: $\leq$ 0.1ms
Major use cases	Fine medicine, Intelligent disaster prediction, Surreal VR, 3D videos,	Holographic projection, Tactile and haptic, Autonomous driving, Internet of nano-bio Things, Space travel	XR (VR/AR), Brain commun. Connected robotics & autonomous systems	Teleportation, eHealth, VAR, Industry 4.0, Robotics, Autonomous, transportation	High precision Manufacturing, Smart environment, Holographic commun.	Remote surgery, Haptic Commun., Massive IoT enabled smart city, VAR, Autonomous driving, Automation and manufacturing
Key enabling technologies	Ultra massive MIMO, OAM-MDM, Super flexible integrated network, Multi-domain, Index modulation	THz commun., Holographic beamforming, Quantum commun., AI/ML, LIS, VLC, Blockchain	Tinycell, Ubiquitous network, Energy transfer & harvesting, Transceiver with integrated frequency bands, Smart surface	THz commun., VLC, ML, 3D networks, Cell-less architecture, Energy harvesting, NFV, Backhaul	Novel network architecture, VLC, AI at network edge, Battery-less devices, THz commun., Distributed security	Pervasive AI (+game), Smart environment, Fluid antenna, Radar-assisted context commun., Cell-free networks, Quantum commun., WPT, OAM, VLC, Blockchain, THz commun.

TABLE III
A COMPARATIVE STUDY AMONG VARIUOS 6G APPROACHES

the environment (see Fig. 2), and predict suspicious activities. In addition, methods like physical layer authentication which relies on users' behavioural data will be possible. The general contextual data gathered by UEs will also assist the network to serve better by predicting UEs' next moves.

C. Cell-Free Networks

In 6G, the full potential of unmanned areal vehicle (UAV) wireless networks or dronecells will be realized. Their application will be widely extended to mobilizing the network resources and integrating with cell-free massive multiple-input multiple-output (MIMO) to achieve truly cell-free networks where arbitrarily small latency may be obtained. To take full advantage of the fluid cells formed by UAVs, the optimization for resource allocation, trajectory, content caching and user association will be achieved jointly. Also, in 6G, UAVs will not only serve as flying base stations to provide radio coverage but can also be content providers and computing servers. There will be a lot of synergy with other emerging technologies. For example, AI will take the network usage data to learn and dynamically find the best paths for the UAVs and optimize their other parameters. This will inevitably lead to dynamic reconfigurations of the network topology. In addition, UAVs will benefit greatly from WPT and solar power technologies that can keep them moving all the time, while UAVs will also help support service-based network slicing.

D. Programmable Materials and Environments

Metamaterials-based antennas have been researched for two decades, but are not yet making an impact in mobile communications. 6G will see metamaterials-based antennas become the norm for UEs, permitting the massive MIMO technology to be adopted even at mobile phones as well. The maturity of metamaterials-based antennas will also make small-sized highly efficient wideband antennas possible, which gives the hardware flexibility that the 6G Mitola radio needs.

Another new form of antenna technology, which will come to light in 6G, is fluid antenna [7], made of conductive fluid, metal fluid or ionized liquid that can be shaped to any desirable form to suit the radio propagation environment [8]. The fluidic structure breaks the boundary between the pre-defined antenna hardware and signal processing, and allows to optimize its position and shape for extraordinary diversity and multiplexing gains, while having the ability to reduce the electromagnetic fields (EMF) exposure by adapting to human gesture in the case of mobile phones, based on the environment and the needs at any given time. Presumably, a single software-defined fluid antenna can provide the rich diversity that only massive MIMO antennas could achieve, while enjoying the flexibility to alter its shape, size and position to fully utilize the surface of a UE.

Software-defined materials (SDM) can actually be used to design large intelligent surfaces (LIS) to enable programmable wireless environments as well as for enhancing the coverage area of ultra-small cells [10]. By doing so, it is possible to control the propagation environment by altering its electromagnetic properties. For example, SDM can be laid on walls to provide insulation for unintended radio signals as shown in Fig. 3 [10]. LISs on buildings or in indoor environments are predicted by many to make their mark in 6G.

Programmable metasurfaces indeed can do much more than simply altering propagation environments. They could replace the design architecture of wireless transceivers entirely. Recent results reveal that a metasurface can be programmed to vary the phase, amplitude, frequency and even OAM of an electromagnetic wave, effectively performing the modulation

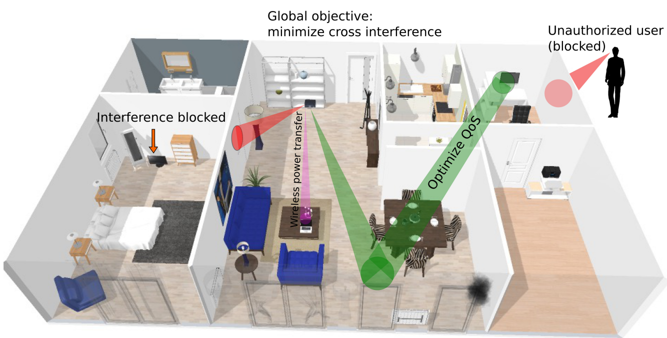

Fig. 3. A programmable radio environment using SDM.

of a radio signal without a mixer, and RF chain [11]. This alternative technology will be quite disruptive and depending on its progress, we may see its operation as an enhancement of 6G, if clear benefits can be materialized.

E. VLC

VLC is a special form of optical wireless communications and uses white-LED to encode data in the optical frequencies and some works have suggested that each link can achieve up to 0.5Gbps data rate [12], hence a good candidate to meet the data rate requirement of 6G. We speculate that VLC will be especially useful in vehicle-to-vehicle (V2V) communications where car's head and tail lights can be used as antennas for 'control and coordination' data communication. VLC will also be useful in scenarios in which traditional RF communication is less effective such as in-cabin Internet service in airplanes, underwater communication, healthcare zones and etc.

F. WPT and Energy Harvesting Based Battery-less Devices

WPT has not made it in 5G but in 6G, it will finally shine for a number of reasons. First, communication distance will be much shorter, making WPT meaningful. Second, to enable IoIT, there will be massive deployment of nano-biosensors which may operate under a battery-less architecture and will require to be excited by external energy sources remotely. Energy scavenging from ambient RF signals will become a viable power source for low-power applications, while energy harvesting technologies continue to advance.

G. OAM Communication

Exploiting polarization diversity and OAM mode multiplexing, it has been demonstrated that very high capacity wireless communication systems can be built to work over a distance of a few meters. The performance is particularly promising at a relatively short distance which can be useful for industrial automation. A mmWave OAM system in [13] was reported to have achieved more than 2.5Tbps rate with spectral efficiency of 95.7bps/Hz. This can be a lucrative technology for Industry X.0 as well as for end connectivity for holographic projection in IXR environments, envisaged as key 6G use cases.

H. Quantum Communications and Networks

Quantum communication is another promising technology which is likely to contribute considerably towards two essential criteria of 6G, namely extremely high data rate and security. The inherent security feature of quantum entanglement that cannot be cloned or accessed without tampering it, makes it a rightful technology for 6G and beyond systems. A number of works already demonstrated initial practical implementation of quantum key distribution (QKD) and associated protocols. Another attractive feature of quantum communication is that it is suitable for long distance communication. Nevertheless, current repeater concept is not applicable for quantum communication as entanglement cannot be cloned. Satellites, high altitude platforms and UAVs may be adopted as trusted nodes for key regeneration and redistribution. In terms of designing quantum devices, single photon emitter device has already been realized which currently works at few degrees above the absolute zero temperature. Much work is still needed to make it operate in normal temperatures. It may be a long shot to see much of an impact of quantum communication in 6G.

I. Blockchain Technology

Blockchain will likely play a major role in securing and authenticating future communication systems, thanks to the unique advantage of distributed ledger technology. It offers a number of benefits including decentralization, transparency with adequate privacy and alteration-proof authentication. Both decentralization and transparency ensure faster processing which is crucial for 6G systems. As mentioned before, network resources will be virtualized and therefore blockchain will play an important role in simultaneous resource allocation and authentication. Also, in the future, security will need to be highly adaptive depending on the location, device capability and application. Healthcare data, for example, needs to be extremely secure and private while emergency responses may require quick access to those data via 6G systems and thus it needs to ensure that a person has the right level of access to the data on the fly. Blockchain will also be very useful as an enabler in other cases such as cloud storage, mobile edge access, and etc. However, significant research needs to be done to avoid delay caused by the blockchain processing to ensure that constraints of latency-critical applications are met.

V. CHALLENGES

As seen in Table I, 6G looks for several orders of magnitude improvements over 5G in all aspects. Here, we highlight a few hurdles, where major efforts will be needed.

A. Providing Terabit Data Rate Ubiquitously

The biggest challenge in 6G will be to provide massive data rate in various parts of the network. The recently formed ITU focus group technologies for networks 2030 (FG NET-2030) raised a concern that fixed access networks capabilities are already lagging behind emerging 5G systems. It is anticipated that access networks for backhahul traffic will struggle to cope with unprecedented data growth and other quality requirement unless necessary steps to boost the research effort are initiated. Free space optical communications and quantum communications are the hopefuls for 6G backhaul but those technologies have a number of challenges to overcome before a realistic deployment including appropriate circuitry design, mismatch between RF and optical domain and so on.

For various applications, higher frequency bands are anticipated along with technologies like OAM and VLC. However, these technologies require to overcome significant challenges such as transmission distance, obstacles, absorption and compatibility/interfacing with other techniques.

B. Modelling Sub-mmWave and THz Frequency Channels

An obvious way of supporting massive increase in the data rate requirement is to increase the bandwidth and go up the frequencies. Initial discussion indicates that frequencies in the range of THz and above will be considered for 6G. These spectrums will be utilized in very short range communication or 'whisper radio' [14]. Nevertheless, the susceptibility of the THz band to blockage, molecular absorption, sampling and circuits for A/D & D/A conversion and communication range is among the major challenges that need to be addressed in the coming years. Another issue is that at higher frequencies, the antenna size and associated circuitry become miniaturized and are difficult to fabricate on chip while still ensuring noise and inter-component interference suppression. On the other hand, the exact propagation characteristics in these bands is not well understood, although there have been a few recent attempts to address these bottlenecks. THz technologies are still in their infancy. Major challenges with THz source/detector, adequate power generation, THz modulator/demodulator as well as THz antennas are still yet to be tackled. Furthermore, appropriate channel sounding and measurement devices need to be designed which is quite challenging due to limitation of properties of the materials used in the existing devices.

C. Resource as a Service (RaaS)

The emergence of software defined networking (SDN) and network function virtualization (NFV) sparks a shift to service oriented and integrated resource distribution which is known as RaaS. The concept of traditional physical resources from management point of view will gradually diminish and most of the network element will be fully virtualized where fog networking, mobile edge computing and network slicing will play a key role. In 6G, new types of resources will emerge. For example, software-controlled metasurfaces and SDMs will be considered as part of the network resources and therefore the new mechanism needs to be designed to incorporate them as manageable resources which will make the resource management much more computationally complex and resource intensive. Thus, one trend of development for NFV in the 6G cycle will include network slicing with SDMs and programmable metasurfaces, from machine learning-enabled cloud random access network (C-RAN) to fog-RAN. Nonetheless, mapping a high level service abstraction to hard network components and mapping of network functions and infrastructure to vendor implementations as well as end-to-end management and orchestration mechanisms are very difficult tasks, and significant progress will need to be made if RaaS appears in 6G.

D. High-Capacity Low-Power Devices

Every generation of mobile communications has been defined by the UE capability. This will be more so for 6G as 6G will be AI-led and require high computational power to run the AI algorithms. Therefore, UE will be more power hungry than ever. Energy efficiency at the device level will once again be a KPI in 6G. Conventional transceiver components are mostly based on semiconductor materials like Silicon (Si) and Gallium Arsenide (GaAs). These devices are not energy efficient and produce excessive heat. Since the maximum operating frequency of CMOS transistors has not improved from around 300GHz in the manufacturing process after 65 nm in line with miniaturization, 300GHz-band amplifiers with a CMOS integrated circuit are extremely difficult to realize. This means that they are not capable of supporting computationally intensive and ultra fast applications for 6G. Thus, new devices need to be designed based on new materials which have the characteristics to support the need for emerging systems.

There are some promising approaches which may revolutionize the domain. One such concept is superconducting spintronics which will enable ultra low energy computation by combining superconductivity with magnetism. However, significant research is needed to operate it in room temperature. There should be significant work focused on designing super heat sinking capacity which is crucial for 6G systems.

E. Security and Authentication

With over 50 billion UEs and IoT devices connected everywhere operating with different levels of capability, 6G will need a holistic approach to secure the sheer volume of mobile data across a diverse set of platforms and comply with the strict privacy and security requirements. The hope is that 6G technologies will make the security of mobile devices virtually unbreakable with flexible hardware requirements.

VI. CONCLUSIONS

As 5G is in its launching phase worldwide, discussion has already begun to shape what 6G may be. There are already high-profile initiatives around the world aiming to develop technologies for 6G, such as 6Genesis of Finland and TOWS for 6G LiFi in the UK, among others. While it is too early to define 6G and there are inevitably omissions in any of such discussion, this article has taken a bravery approach to identify possible enabling technologies for 6G and describe the features they bring beyond the capability of 5G. Our 6G vision presents a genuine realization of Mitola radio, which has exceptional awareness of the environment (by radar technologies) to make decisions using superb intelligence (by collective AI), with a rich action space to adapt itself in many forms (by intelligent structures, Li-Fi, WPT and energy harvesting, etc.). Additionally, OAM and quantum communications may appear in 6G if sufficient advances are made. This article has also discussed the limitations of 5G that form the basis of our 6G vision. We have attempted to present some 6G example use cases which are natural extensions of the 5G use cases and scenarios. We anticipate that as 5G is being put into service, new use cases will emerge and the industry will find more ambitious and challenging scenarios. Lastly, we like to add that 6G will see a shift from the electronic era of 5G to the optical and photonics era, but this deserves a separate discussion.

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