How Crucial Is It for 6G Networks to Be Autonomous?

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Invited Paper

Abstract—The sixth generation (6G), unlike any of the previous generations, is envisioned by 2030 to connect everything. Moreover, in addition to the new use cases 6G is expected to support, it will need to provide a superior performance over 5G. The global connectivity, large network dimensions, users heterogeneity, extremely low-power consumption, high throughput, ultrahigh reliability, efficient network operation and maintenance, and low-latency requirements to be met by future networks inevitably necessitate the autonomy of 6G. Intelligence, facilitated mainly by the advancement of artificial intelligence (AI) techniques, is a key to achieve autonomy. In this paper, we provide a bird’s-eye view of 6G, its vision, progress, and objectives. Furthermore, we present some technologies that would be mainly enabling intelligent globally connected world. In addition to discussing the role of AI for future wireless communications, we, unlike any other review papers, provide our original results which give early evidence for the viability of achieving 6G networks autonomy through leveraging AI advances. Furthermore, we, very importantly, identify 6G implementation challenges and key innovative techniques that promise to solve them. This article serves as a starting point for learners to acquire more knowledge about 6G and also for researchers to promote more development to the field.

Index Terms—Artificial intelligence (AI), autonomous networks, blockchain, non-orthogonal multiple access (NOMA), quantum communications and computing, sixth generation (6G)

I. INTRODUCTION

Recently, as the fifth generation (5G) standard has been getting finalized, and in order to set unified precise targets and roadmap for the sixth generation (6G) communication networks, researchers from industry and academia have begun to envision and extensively discuss its key values and use cases [1]–[7].

A. 6G Vision

The 6G is depicted, in its first global vision, as a framework of different services such as sensing, computing, caching, imaging, highly accurate positioning and mobility, radar and navigation integrated with the main communication services the previous generations provide. 6G will be an autonomous ecosystem that connects everything through multidimensional networks that provide services in the ground, air, space, and underwater aiming to provide quality of not just service but life. Benefiting from smart sensory environments, 6G will be driven by a variety of verticals including factories, automation and transportation, and healthcare. 6G is predicted to be motivated by potential new applications for which the currently deployed 5G infrastructure is not expected to support [8]. A main domain of these applications is the connected robotics and autonomous systems that include self-driving cars, drone delivery systems, and autonomous robotics. These applications will get the full use of the multidimensional network structure, and artificial intelligence (AI) capabilities to be offered. Other domains include extended reality (XR), blockchain and wireless brain-computer interaction based applications. Different requirements for these applications and their corresponding use cases set different trends and research directions towards 6G. For example, autonomous systems applications require ultra-reliable, low-latent, and secure communications. There are a number of applications, e.g. holographic communications, that are bandwidth intensive and thus require opening up new and wider spectrum such as terahertz (THz) bands [9]. On the other hand, other use cases involve communications between multiple small devices that mainly work on batteries set the trend for energy sustainability. More details about the requirements demanded, and technologies promising for realizing the 6G are presented in this article.

B. 6G Objectives

Spectrum and energy efficiency, peak data rate, user data rate, capacity per unit volume, connectivity density, latency, reliability, and mobility are some of the key performance indicators (KPIs) evaluating 6G networks. Technical objectives for these KPIs, set mainly based on requirements, trends, and applications, are summarized and compared to their counterparts in 5G as follows:

- Up to 10 Tbit/s of peak data rate (1000 times that of 5G) to be targeted [2].
A user data rate of 1 Gbit/s (10 times 5G) or higher.
- No more than 100 µs (1/10 5G) of latency is allowed. 10 times lower latency in certain cases needs to be maintained [2].
- Providing services to $10^7$ devices/km² resulting in 10 times of the 5G connectivity density.
- Volumetric spectral and energy efficiency 100 times the per unit area efficiency in 5G [8].
- Reliability of seven 9s as opposed to that of five 9s in 5G.
- Support mobility up to 1000 kmph, as the 6G is foreseen to support airline systems and high-speed railways. The 5G, however, was intended to support less than half of that.

In this paper we discuss the key innovative technologies promising to meet some of the aforementioned objectives.

C. Paper Organization

This paper is organized as follows. Section II contains some of 6G enabling technologies’ basic principles and compelling features, and discusses the need of integrating them with other techniques to get the most out of them. In Section III the role of AI in maintaining intelligent and hence autonomous 6G network is discussed. The Section, in addition, presents some of our simulated experiments results that demonstrate the effectiveness and superiority of AI-enabled networks. In Section IV we cover some of future networks'challenges, possible solutions, and related open research directions. Concluding remarks are given in Section V.

II. 6G ENABLING TECHNOLOGIES

The capability expansions, performance improvements, variety of new trends and service classes that need to be guaranteed and supported by 6G require the incorporation of disruptive technologies. In this section we present some of 6G promising technologies.

A. Above 6GHz Communications

The sub-6 GHz band becomes highly congested due to heavily used frequency resources. It no longer can support massive increases in communication capacity. Allowing accessibility to higher frequencies and bandwidth, millimeter wave (mmWave) technology has been emerging to overcome the lack of spectrum issue. Facilitating the 6G high-rate high-mobility use cases (e.g. autonomous vehicles), mmWave is considered to be one of the 6G enabling technologies [9].

MMWave communications, ranging from 24 GHz to 300 GHz, will be one of the leading candidate systems for future wireless communications [10]. MmWave achieves peak data rates of 10 Gbit/s or more with full-duplex capability, far exceeding the lower microwave frequency limit of 1 Gbit/s [11].

Despite its benefits, nevertheless, atmospheric absorption highly attenuates mmWave signals. Using Friis Law [12], one can determine an obtained power, $P_R$, at a receiver in free space environments (one may refer to [13] for more generalized environment) located at a distance $d$ apart from a transmitter sending a signal with wavelength $\lambda$ and power $P_T$ as described by the following equation:

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2,$$

where $G_R$ & $G_T$ are the receiving and transmitting antenna gain respectively. We can notice from the equation that under the same distance and antenna settings as microwave signals below 6 GHz, the free space path loss, i.e. $P_T/P_R$, for mmWave signals is much higher. This shows that using mmWave frequencies reduces the transmission distance which is a huge disadvantage in mmWave systems. Due to their associated signals’ short wavelengths, nevertheless, mmWave technology can be integrated with large-scale multi-antenna arrays, e.g. super massive (SM) multiple input multiple output (MIMO) [14], and beamforming techniques allowing for high antenna gain and highly directional communications hence extending communication distance, enhancing security, and improving interference immunity. Another major technical challenge for mmWave is the blockage effect. Rending to their abilities in providing line-of-sight (LoS) links with a high chance, aerial base stations (BSs) and the resultant potential 6G 3D networks can decrease the impact of the aforementioned issue. Furthermore, fusing mmWave with machine learning (ML) and deep learning (DL) techniques to make data-driven decisions allow getting the best out of it [15]–[17].

Commercial mmWave communications have become a reality with the standardization of 5G, however their potentials would fall short of many new application, such as 3D gaming and XR [8]. Hundreds of gigabits per second to multiple terabits per second data rates are needed for these applications which will require some other innovative solutions. This leads us to THz communication systems which are widely recognized as the next step of wireless communications research. The 0.275 to 3 terahertz band spectrum is the main part of the THz band, which ranges from 0.1 to 10 terahertz, to be used for cellular communications, according to International Telecommunication Union Radio Communication Sector (ITU-R) guidelines [18]. Such abundance in spectrum portend to offer extremely high data rates [9].

Despite their features, however, there are many open research issues in THz radio communications such as small propagation range due to high propagation and molecular absorption losses, and THz transceiver design that will need to be addressed to make it realizable. To achieve a successful THz deployment and operation in 6G networks, nevertheless, pencil beams [19], [20], and holographic surfaces [21] solutions are to be considered for overcoming THz issues. In spite of that, the coexistence of THz systems with sub-6 GHz and mmWaves is necessary, especially in dynamic environments with non-line-of-sight links where lower band technologies can offer higher reliability and longer ranges.

B. Non-Orthogonal Multiple Access (NOMA)

Traditional orthogonal multiple access (OMA) schemes
may struggle to accommodate the massive number of 6G connections, since these techniques divide a resource block (RB), time, frequency, or code, between users equally without taken into consideration the variations of their channel conditions. Capitalizing opportunistic channel conditions, however, NOMA assigns different amount of power over same RB, where worse channel gain translates into a higher power. As a result, on the contrary to OMA, NOMA exploits the dimension of power domain to utilizes a RB for serving multiple users simultaneously. NOMA, as a consequence, offers not only higher spectral efficiency and throughput but also better fairness, lower service latency, and higher connectivity density \(^{22}\). Thanks to superposition coding (SC), which encodes multiple signals with distinct power into a single signal at a transmitter, and successive interference cancellation (SIC), implemented at a NOMA receiver to distinguish a signal from other signals, which make the NOMA idea possible.

NOMA, nonetheless, has some limitations, such as receiver computational complexity, BS channel state information (CSI) prior knowledge, and performance degradation as number of users increases. Due to these issues, the 3rd Generation Partnership Project (3GPP) has deferred the use of NOMA for next-generation networks, where most of these limitations will not be a concern, and given up on making NOMA an option for 5G \(^{23},^{24}\). To benefit from the superiority of NOMA in fairness, latency, throughput, and connections density in the 6G networks, NOMA will be expected to be implemented in merged with some other technologies like mmWave, and aerial BSs. Optimizing a network combining these technologies, nonetheless, would be a complex non-convex problem that is of a challenge to be handled with traditional mathematical solutions \(^{15},^{16}\), however, we will discuss the viability of managing them autonomously by using the power of AI.

C. Unmanned Aerial Vehicle (UAV)

Aerial BSs, or UAVs, are emerging as one of the 6G essentials as they can provide high data rates and global wireless connectivity. UAVs enjoy exclusive features such as ease of deployment, high LoS links probability, and large degree-of-freedom provided through their controlled mobility \(^{25}\). UAVs can be deployed to offer wireless connectivity in case of emergencies such as natural disasters, overcome last mile issues, enhance capacity, replace terrestrial BSs, etc. Allowing UAVs to adaptively relocate according to environmental changes and users’ demands is one of the most important UAV features. The goal of connecting the unconnected to be met by the 6G will be made possible by aerial BSs as their deployment are much easier and more economical than that of their terrestrial counterparts, especially in rural areas. Rending to their ability to connect with low earth orbit (LEO) satellites, CubeSats, and terrestrial BSs, UAVs are also envisioned to be one of the main technologies to realize the 6G multi-dimensional network. Managing UAVs’ placement and resource allocation simultaneously, however, is a challenge that has to be addressed in order to get the most out of their resultant 3D networks. AI advances are promising, nonetheless, in managing the UAV networks autonomously yet efficiently and effectively \(^{15},^{16}\).

D. Quantum Communications and Computing

Quantum-assisted communication is a novel field that can be viewed as one of the cornerstones for future multi-state networks. Rendering to their capabilities in solving problems exponentially faster than their classical counterparts, quantum computers (QC) will bring a new era in telecommunication. Their working principle is based on essential concepts of quantum mechanics such as superposition, entanglement, and no-cloning theorem \(^{25}\). Constructing independent copies of quantum information is impossible, as the no-cloning theorem states. Thus, offering high communication security which should be a key feature of 6G. A qubit, quantum analogy of a classical bit, represents a two-level quantum system, where each level is called a state. Instead of representing zero or one only, however, a qubit can be in a superposition, linear combination, of both. That means upon measurement, a qubit will be found with some probability in the one or zero state. For n qubits, a quantum computer can work with \(2^n\) quantum states simultaneously. This parallelism makes quantum computers potentially useful in applications that require the processing of big data. Many efforts have been done by the research community to investigate on the involvement of quantum speedups in various communication areas. The authors in \(^{27}\) for instance have proposed and presented a number of quantum search algorithms that are particularly applicable to wireless communications. Quantum computing merged with different AI techniques, e.g. quantum machine learning (QML), has promising potentials in solving challenges in many aspects of 6G networks and beyond \(^{28}\).

E. Blockchain

Blockchain is considered as a technology breakthrough in the recent years that is expected to have an important role in achieving 6G objectives \(^{29},^{30}\). Blockchain, which is simply a database structure, offers multiple key characteristics that are useful when used with certain applications. Blockchain stores data in blocks called datablocks, each datablock is attached to the previous one forming a chain of blocks. This chain is replicated and stored across different nodes that form a network. Once a data update request is initiated, it is broadcasted to all nodes where they use their available computational power to verify that it follows some pre-defined rules, once verified, the datablock is linked to the previous one in the chain. The described structure along with the operation method enable the blockchain technology to be used in applications that require high level of security, where changing one datablock in a certain node can be easily detected once the other nodes cross-reference each other. Other characteristics provided by blockchain-based systems are their scalability, where they can be used for 6G to overcome scaling limitations of centralized conventional networks. Transparency is also
a key feature of blockchain that can be used for dynamic resource management across different small scale operators since the records can be set to be accessed with equal rights without the need for a third party. The distributed architecture of blockchain is also beneficial in facilitating decentralized systems and thus eliminating single point failures of previous generations systems. Consequently, blockchain was proposed to be used in different areas of 6G such as blockchain-based resource management frameworks [31], and blockchain-enabled architectures for UAV networks to ensure security and privacy with enhanced network performance [32].

The aforementioned technologies promise in meeting some of the 6G objectives and enabling corresponding features including throughput, latency, connectivity, security, etc. Other technologies, whether they are evolving from the 5G or exclusive to 6G, for example large intelligent surfaces [33] and holographic beamforming [34], are out of the scope of this article.

III. INTELLIGENCE OF FUTURE NETWORKS AND AUTONOMY

In addition to communication, 6G will, exclusively, offer other services like computing, control, localization, sensing and cashing for very heterogeneous use cases in a highly complex and dynamic environment. Organizing resources of 6G networks sustainably while meeting desired KPIs will inevitably need to be done autonomously. Leveraging AI advances is a must in achieving networks self organization. Rendering to the huge gain observed from incorporating AI techniques in optimizing wireless networks, research community has been giving them more and more attention [35]–[37]. Through learning and prediction, AI will be an efficient solution for achieving the convergence in managing and allocating 6G network resources for various services [2]. Softwarization [38], cloudization [39], virtualization [40], and slicing [41] which are main techniques for 5G network orchestration, will be also expected to be important characteristics of 6G autonomous network. AI enabled however, AI algorithms will, in addition, be implemented at network edge, for example at the smart wearable devices, enabling collective intelligence and distributed autonomy.

When it comes to optimizing resources (time, spectrum, space, beam, mode, power, and code) of multi-level and multi-dimensional networks with massiveness of connections, AI does not just outperform legacy techniques, it however emerges as a main management technique for the following reasons:

- Conventional design methods which are built based on mathematical and statistical models require perfect system characteristic knowledge which can not always be accessible.
- Traditional methods based solutions are not always optimal as their corresponding decisions are taking only according to current input and no account is taken for future information.

Rending to their high ability in learning, predicting patterns, and taking decisions accordingly, AI techniques, on the other hand, lead to enhancing wireless network performance in situations where legacy techniques fail [15], [16], [42], [43].

Managing a network that integrates mmWave, NOMA, and UAV technologies such that the power and beam allocation, and UAV placement are jointly optimized, for example, is definitely a complicated task and traditional methods fall short to handle [15], [16]. Using novel-AI solutions, we accomplished in [15], [16] to not only solve the problem without the need of disjointing it into sub (unrealistic) ones but also outperform some other existing heuristics derived by legacy methods e.g. [44]. We, more specifically, proposed a deep reinforcement learning (DRL) [45] based framework that simultaneously places a UAV in a 3D space and allocates NOMA power among users associated in clusters such that average sum of users’ data rate is maximized and certain fairness criteria is met. In this article, we present some of the simulation results as the UAV is being trained to learn the optimal decision while serving a total of four users, where each two are associated with a certain cluster. The ith user will be denoted by USERi and a decision interval will be referred to as an episode. More details about the framework and simulation setup are available in [15], [16]. Fig. 1 shows 100-episode moving of power allocation, channel gain, and average sum rate of our proposed framework, denoted by DRL, as they vary over episodes. In Fig. 1(c) we include the average sum rate achieved by the state of art (SoA) suggested in [44] and denoted in the figure by SoA. We can notice that the DRL average achievable sum rate converges to 23.5 Gbit/s which represents a 57% improvement compared to 15 Gbit/s given by SoA. To be able to determine a mathematical solution for the optimization problem, the authors in [44] ended up restricting the UAV placement into a 2D plane. In contrary, our DRL framework allows 3D UAV mobility without making any confines. Hence, the gain in performance our AI based technique offers is intuitive. Furthermore, we can notice that DRL managed to recognize the NOMA power allocation order, by allocating the far user (the one with the poor channel condition as depicted in the top of Fig. 1(a) and (b)) more power (as exhibited in the bottom of Fig. 1(a) and (b)) than the near one without even imposing that in the algorithm. The resultant choice of order is crucial for the work of SIC, as discussed earlier, and is the best to get the most out of NOMA. The power allocation related decision was made intelligently autonomously by the UAV through the judicious algorithm design with the goal of improving total sum rate and maintaining a certain fairness level. The presented findings do not only show how compelling AI schemes are in enhancing performance, but also their abilities in achieving autonomy and hence realizing future networks vision.
IV. FUTURE NETWORK DEPLOYMENT CHALLENGES AND SOLUTIONS

A. Complexity

The superior performance of 6G and the ability to achieve full autonomous networks requires high computation capabilities, which will be a challenging task even for most powerful computers.

Despite its extremely wide spectrum, mmWave and THz technologies, for example, require a highly directional transmission which incur a substantial overhead. Searching in a very large angular space is essential for achieving high beamforming gain and thus, reducing the initial access performance. The process of aligning beams between two communicating entities leads to communication and computational overhead. The good news, however, is that ML and DL-based initial access methods have the potentials in reducing such overhead [46], [47]. Moreover, the immense power of quantum computers in speeding up ML algorithms can be investigated not only for beam alignments, but also for some other services such as users tracking [28].

NOMA, even though it enjoys features that are important for ensuring meeting number of 6G objectives, is still limited by the high computation complexity incurred for SIC estimation, especially, as stated earlier, if number of users is high. Moreover, clustering and allocating power for mobile users in mmWave-NOMA demand high computational power, as they need to be updated in real time. Emerging AI techniques can overcome some of these limitations [48].

With the ever-increasing demand for high capacity, implementing multi-user multiple input multiple output (MU-MIMO) will be impractical. The utilized detection algorithms suffer from high complexity which increases exponentially with the number of users and data rate. [49] is one of the few works that proposed a solution for MU-MIMO complexity problems and showed its effectiveness by implementing it on a real quantum computer. With very low bit error rate considering different modulation schemes and channel conditions, the authors of [49] managed to achieve MU-MIMO signal detection, just in order of microseconds, for a number of users and data rates that are unfeasible to handle in classical computers.

The necessity for high computational power and parallelism suggests that quantum machine learning can be a crucial candidate in 6G networks and beyond.

B. Security

A number of applications including autonomous system such as healthcare, robotic, and vehicular communications demand a very-high level of security. Classical cryptographic methods would fail short with the emerging quantum technology [50]. Through some of its attributes including anonymization, decentralization, and untraceability, blockchain technology, however, can come as a solution for security vulnerability issues [51]. UAVs for example are emerging not just as aerial BSs, but also to provide a variety of other applications such as logistics, surveillance, disaster management, and rescue operations. Securing such UAV networks, which will eventually be transformed into Internet of UAVs, will inevitably require leveraging of blockchain technology. Addressing security issues for which the unique 6G networks may be vulnerable to, will certainly require a lot of attention from the research community.

V. CONCLUSION

In this article we outlined the 6G vision and requirements. We presented some of 6G enabling technology. We also emphasized on the need of 6G network autonomy and hence intelligence. In addition, considering some of our numerical analysis, we emphasized on the necessity of integrating AI techniques in the resources management of future networks. Furthermore, the article presents some open research problems and challenges in realizing future networks objectives and trends, and discusses the potentials of some emerging technologies in solving them.
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