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Quantum Machine Learning For Next-Generation Communication Systems

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Abstract: As we see communication systems transform at an incredible rate of change there is a great demand for smart, secure and scalable solutions. In steps Quantum Machine Learning (QML) which is that which we see as a very powerful new approach which puts together what quantum computing has to offer with traditional machine learning thus bringing in a new age of communication networks. This paper looks at how QML may put forward solutions to some of the main issues in the next generation of networks which include 6G and beyond in terms of improving channel estimation, enhancing error correction, and optimising resource management. Also included in the picture are what QML's features of quantum parallelism and entanglement bring to the table which in turn have the promise of QML out performing classical models in areas such as signal processing, predicting network traffic, and improving in the field of cybersecurity. Also we see a report on the present state of quantum hardware and algorithm development as they pertain to how this may play out in real world network settings. At the same time we look at present issues which include hardware limitations, quantum noise, and the issue of developing very efficient algorithms which we also put forward possible solutions to. As a whole the report puts forth that QML may in fact play a very transforming role in the future of communication technologies in which we see networks becoming smarter, faster and more secure.[3].

Keywords **- Quantum Computing, Machine Learning, Next-Generation Communication, 6G, Quantum Algorithms, Network Optimization..**

I.INTRODUCTION

As wireless communication technology rapidly evolves, the demand for systems that are more efficient, secure, and adaptable continues to grow. While traditional machine learning (ML) has made valuable contributions to this space, it often hits a wall when it comes to processing power and scalability. This is where Quantum Machine Learning (QML) comes into play— offering a fresh, powerful approach that could redefine how future communication networks operate.

Quantum computing works on fascinating principles like superposition and entanglement, which allow it to process vast amounts of information much faster than classical computers. When combined with machine learning, it significantly boosts capabilities in areas like signal processing, decision-making, and optimization. This blend opens doors to solving some of the toughest challenges in today's communication networkss.

One of the standout benefits of QML is its ability to improve channel estimation and implement more advanced error correction methods. Unlike traditional models, which often struggle to adapt in real time, quantum algorithms bring more accuracy and speed—leading to better overall performance and reliability in wireless networks.

Security is another area where QML shows incredible potential. Quantum-based encryption methods are nearly impossible to break, which means data can be transmitted with a much higher level of security. On top of that, QML-powered systems can detect unusual network activity in real time, helping to prevent cyber threats before they escalate.

Of course, like any emerging technology, QML comes with its own set of challenges. Issues such as limited access to quantum hardware and the effects of quantum noise still pose hurdles. However, researchers are actively working on hybrid approaches that combine classical and quantum computing to get the best of both worlds. As this technology continues to develop, QML is expected to play a transformative role in building smarter, faster, and more secure communication systems for the future.

II. CHALLENGES RELATED TO EMERGING WIRELESS TECHNOLOGIES

With the emergence of these new wireless technologies come unprecedented challenges that need to be addressed to ensure successful deployment and operation. In the forthcoming discussion, we will first outline overarching challenges that arise with the advent of emerging wireless technologies, followed by a discussion of specific solutions based on artificial intelligence (AI) that can effectively tackle these challenges.

1) TOWARDS NEXT-GENERATION WIRELESS COMMUNICATIONS

5G is rolling out now and is anticipated to be rolled out by the 2030s for 6G [13]. With respect to 4G, 5G provides massive enhancements to latency and reliability and a three-times increase in spectral efficiency, supporting a massive number of user connections and abundant services, such as tactile Internet and augmented & virtual reality [14], [15]. The next leap, 6G, is anticipated to provide a ten-fold greater improvement in spectral efficiency and a ten-fold greater improvement in energy efficiency against 5G [15]. With the birth of such promising technologies as Terahertz communications, 6G is expected to have an unprecedented advantage from the system's overall bandwidth, with more than 300 MHz bandwidth [15]. 6G will also target an even higher degree of device connectivity with a connection density of more than 107 devices per square km [14]. Even more exciting, 6G will change the paradigm of coverage with the advent of non-terrestrial networks, functioning not in area-based but in 3D wireless coverage [14]. The above factors provide further impetus for research in emerging technologies along all fronts of wireless communications, especially considering that the growth in traffic will come not only from users' devices but also from machine-type devices [16]. Further details about the vision for next-generation wireless communications are introduced in [14], [15]. An overview of the evolution is illustrated

2) INTERPLAY BETWEEN EMERGING TECHNOLOGIES

Interdependent all previously mentioned enabling technologies will add benefits, among other things to the performance of capacity, energy efficiency, and reliability. For example, previous studies [17], [18] proposed RISs integration scenarios with non-orthogonal multiple access (NOMA) which would improve the spectral efficiency of such RIS-enabled signal partitions among different user terminals. However, the concurrent use of a number of these technologies increases the overall potential complexity involved in the optimization of the underlying parameters. For example: An exemplary picture is given in the case of RIS with power domain NOMA. The parameters include RIS phase shifting, NOMA user pairing, and NOMA power allocation, which will change together to minimize inter-user interference and will improve the performance at the system level.

3) GROWING SCALE OF THE WIRELESS SYSTEMS

The wide-scale wireless communication system can create a surge in the signaling and computational overhead. This would be more pragmatic with regard to RISs and add-on antenna arrays, since, in such cases, a very number of pilot signals are usually required for accurate channel estimation using standard techniques like maximum-likelihood estimation. In particular, RISs and large antenna arrays may require large numbers of pilot signals for accurate channel estimation if conventional estimation techniques, such as maximum-likelihood approaches, are utilized.

4) DYNAMIC WIRELESS COMMUNICATION ENVIRONMENTS

Necessitating adaptive resource allocation strategies is the variability in the environments of wireless communication. Moreover, an increasing number of wireless clients, such as user terminals, IoT nodes, and smart vehicles, requires the allocation of limited network resources, in real time, to the massive number of network devices along with communication reliability and fulfilling the latency requirements in the complicated deployment scenarios [19].

B. AI FOR NEXT-GENERATION WIRELESS COMMUNICATIONS

Hence, there lies a growing urgency to consider alternative techniques for optimization of wireless communication systems in view of the problems cited above. But in recent years, significant strides have been made in AI and ML developments, which have accelerated the impetus for transforming wireless communication systems into natively intelligent systems that can tackle myriad problems [20]. This is brought out in the discussions in the next sub-sections.

1) AI FOR THE INTEGRATION OF DIFFERENT WIRELESS TECHNOLOGIES

Firstly, AI has a possible role in coordinating work among emerging wireless communication technologies such as user grouping design under the merger of RISs and of NOMA [18]. To this end, an ML-based approach is illustrated in [21] to support interactions between RISs and MIMO (multiple-input multiple-output). Specifically, deep-learning approaches were thus adopted to optimize the RIS phase-shifting and the hybrid precoders for MIMO. Furthermore, AI can also come in handy in performance enhancement in heterogeneous wireless communication systems where different multiple access techniques, modulation schemes, and transmission technologies work together to meet the service demands of numerous user terminals.

2) AI TO TACKLE SCALABILITY ISSUES

In addition, AI can tackle the scalability challenge with estimation using poorer information. For example, deep learning can be applied to channel extrapolation, thus requiring fewer pilot signals [22]. Finally, in distributed wireless communication networks with multiple access points, a decentralized or distributed AI framework can be adapted for optimizing the operating parameters of the network in order to avoid the computational and signaling bottlenecks that normally exist in a centralized AI framework.

3) AI FOR ADAPTING TO DYNAMIC ENVIRONMENTS

AI can also be such a necessary tool in adapting to dynamic scenarios of wireless landscapes while achieving reasonable performance levels, which is only possible by conventional analytical techniques [24]. For example, in drone-based wireless communication, when there is a moving U.A.V as an access point, the UAV has to adapt its transmit power and precoding from time to time to maintain the coverage as well as to minimize interference with the related regions. AI can thus equip a global observation of the wireless network, like the coordinates of the network nodes, instant channel conditions, and the number of available transmitters, alongside considering the modifications in the communication network as the movements of the end-users' terminals and the modifications in the propagation environment to dynamically optimize the communication variables such as the transmits precoding and the power control with the help of different AI based approaches like online learning and reinforcement learning [24]. However, the computational complexity of a classical based learning model/algorithm is growing generally in proportion to the dimension of the input data channel state information as well as to the complexity of the learning model, i.e., by the number of layers composing the model, and also by the number of iterations [25]. Although an inference can be done in an acceptable computational time under one trained learning model, the training of parameters in that model may involve lots of iterations comprising a huge number of inferences. This means that a long training duration and a limited applicability of high-dimensional learning models would be achieved; especially under time constraints, following the examples of real-time wireless systems with ultra-reliable low latency communication (URLLC) [26].

C. QUANTUM-BASED AI FOR NEXT-GENERATION WIRELESS COMMUNICATIONS

What quantum computing, on the other hand could do Moreover, it has a great deal of capability for computation to accountfor the needs of future wireless communication systems. Particularly, the number of devices and antenna transceivers shall cause an explosion to the possible diverse combinations and thus result in exceedingly high computational demands for signal detection and channel estimation,, among perhaps other things. 3 D coverage due to the rollout of the non-terrestrial network may pose a few challenges in beamforming, localization, and sensing. Apart from many others, these are the key factors for the future development of 6G concerning the performance measures. To be able to manage future wireless systems, a set of several often computationally heavy variables such as those linked to rate fairness, availability of transceivers, energy consumption, or user throughput shall have to be taken into account. Unlike classical-based computations, which process a string of classical bits each having a value of a computational basis (either 0 or 1), quantum-based computations assume quantum bits, or "qubits", as the smallest unit of computation, each representing a superposition of computational bases enabled by a property called quantum superposition. Thus, processing multiple qubits would leverage other quantum properties such as quantum entanglement, which would allow the state of one qubit to alter the state of another qubit, and quantum parallelism through the powers of simultaneous processing by many inter-connected qubits [29]. The following discusses the motivation behind the use of quantum-based artificial intelligence in the wireless systems.

2) AVAILABILITY OF QUANTUM PROCESSING PLATFORMS

General-purpose quantum processing unit availability has led to recent studies on quantum-based ML. 2206 VOLUME 4, 2023 In fact, companies and research laboratories have rigorously investigated the use of multi-qubit quantum processors, notably IBM [33] and Google [34]. For instance, an IBM quantum computing processor, named "Condor," slated to be operational in 2023 at the time of writing, is expected to operate with a little more than a thousand qubits [35]. Concurrently, D-Wave has been commercially offering its specific-purpose quantum processing units since 2011 [36]. These achievements motivate researchers to investigate quantum-based ML on real quantum computing platforms for various use cases. For example, a recent research work [37] has utilized the D-Wave quantum computing platform for quantum annealing with the aim to optimize vector perturbation for transmit precoding in MIMO systems. Nonetheless, considering the distinct advantages of quantum-based ML, we found a very conspicuous dearth of literature examining the applications of quantum-based ML methodologies that are specifically customized for these upcoming wireless systems, which will be described in the following discussion.

D. EXISTING SURVEYS ON QML UTILISATIONS IN WIRELESS SYSTEMS

1) QML FOR GENERAL APPLICATIONS

Quite a number of QML methods and their applications in different scenarios on prior survey works have been put forward [39], [40], [41], [42]. An overview of different quantum learning models, including quantum neural networks and quantum perceptrons, was presented by the authors in [40]. The same study covered additional quantum learning frameworks, such as quantum adiabatic learning, which uses continuous rather than discrete interference operation-sequential quantum gates-in its operations. In [41], a group of authors discusses several quantum-based models, such as quantum Hopfield networks, and sets optimization parameters for QML schemes. The authors of [42] even discussed some possible applications of QML in some scenarios such as control and object detection. However, when one looks at the research landscape, he will find that there is a notable gap in applying techniques of QML in any optimization of a wireless communication system. Indeed, the bulk of examples available in the literature are confined to the application of quantum-based approaches to the tasks of image processing.

2) QML FOR NEXT-GENERATION WIRELESS SYSTEMS

There were several surveys that highlighted various applications of QML in optimizing wireless communication systems, including [27], which offered an early view on applying QML for future wireless networks. Among other things, the study addressed rising computation requirements as it relates to the size of learning models, such as that in terms of the number of layers of a neural network. Still, better clarity is needed for the reader concerning the practice of using QML for wireless applications, since input encoding, for instance, is not a convention of classical ML. In [27], the authors described some possible applications of ML processes at the different protocol stack layers of wireless communication, including the physical layer-e.g., RIS phase shifting and spectrum allocation-data link layer-for latency constraint, network layer, and application layer, alongside indicating the possible benefits QML may bring, such as reducing the computational complexity. The study discussed in [28] also raises the consideration of integrating quantum-based optimization techniques not only as short and long-term goals for future wireless communication systems, but in realizing that possibility. The consideration of integration of quantum computations and future radio access networks, for instance, for resource management, was also discussed in [28]. Meanwhile, the authors of [39] investigated the likely role of QML in optimality for 6G communication systems, while those of
[38]discussed the probable applications of QML pertaining to enhancement in channel estimation and enabling multi-user communications. Table I illustrates a brief comparison with regard to the subject matter of the current paper and what has been discussed in these previous works.

E. THE PAPER'S CONTRIBUTIONS

Surveys of this type have primarily concentrated on examining the potential applications of QML in wireless communications. However, we do opine that there exists an immediate need for more detailed discourse into specific use cases for demonstrating the viability and usefulness of QML for enhancing wireless communications. Building on the above discussions, the contributions of this paper can be summarized as follows. This study discusses possible benefits and limitations associated with using QML for the optimization of wireless communications and thus fills the gap in literature by surveying current works on applications of QML applied to wireless communications and optimisation. This paper provides a thorough tutorial on QML so that its contributions to wireless communications can be understood and appreciated. The aim is to stimulate researchers to consider QML in their efforts toward optimally designing wireless systems. In this paper, we consider many QML approaches, such as those for dealing with classical-valued inputs, those for producing QML output, and those for optimising parameters. The tutorial would be more beneficial if it included some basics of quantum computing such as quantum superposition and quantum gates for any reader interested in this intriguing area of research. This study also highlights the possible application of QML for the optimisation of wireless communications while providing demonstrations of the feasible implementations with various use cases. Deployment challenges and countermeasures are discussed, as well. The content of the paper is structured to follow. Section II addresses basic concepts in quantum computation and quantum machine learning; in Section III, different optimization methods based on quantum machine learning are discussed. Section IV will then present.

TABLE 1: High level classification of discussed literature on the topics of ML, QC, QML, and communication networks

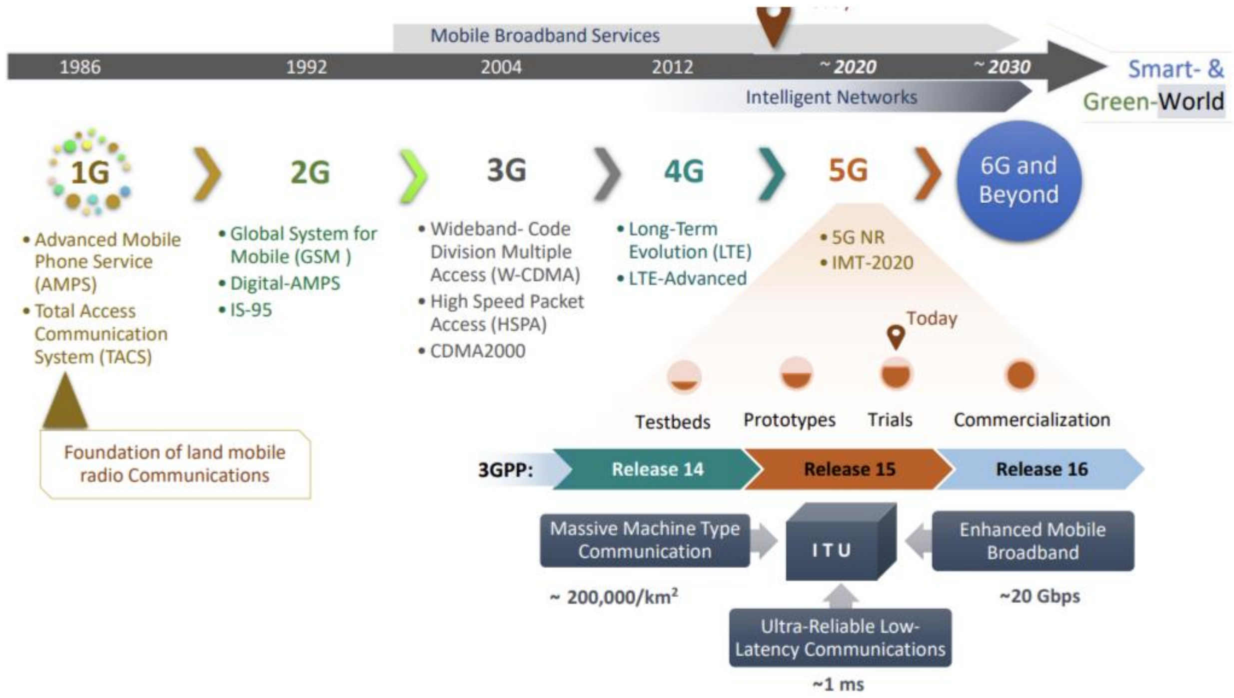
Publications (selective)	Work Scope			
	Machine Learning	Quantum Computing	Quantum Machine Learning	Communication Networks
[1]	✓	✗	✗	✗
[2, 3, 22]	✗	✗	✗	✓
[4, 6, 8, 11–13, 15–21, 23–27]	✓	✗	✗	✓
[28, 29]	✗	✓	✗	✗
[30–38]	✗	✓	✗	✓
[39–43]	✗	✗	✓	✗
[5, 7, 9]	✓	✓	✗	✓
This Work	✓	✓	✓	✓

In this write-up, we seem to open up most of the anticipated service applications for the new mobile communication system, 5G, in addition to the technology innovations that are envisaged in being able to:

And some of these technologies, while quite radical, are not necessarily going to be reached in time for 5G standards, though in many cases they may have matured by then. A: Enhanced Mobile Broadband 5G networks will promise an overall increase in aggregate throughput by 1000 times and 10 times higher individual link throughput as compared to 4th generation (4G) wireless networks [46]. With a target throughput of downlink and uplink of around 20 Gbit/s and 10 Gbit/s, respectively, this will allow services such as UHD video streaming, augmented reality, and TI to be conducted very efficiently. At the physical layer, the technical innovations enabling these rates include communications in the mmWave frequency interval [47], where large bandwidth is in use and thus high data rates can be supported; M-MIMO whereby the number of antenna elements at the base station (BS) is much more than serviced users, making it possible to establish multiple data pipes over the same time and bandwidth resource [48]; and finally, Ultra-Dense Network (UDN) strategy [49] that represents an aggressive deployment of multiple small-cells within a macro-cell. Ultra-Reliable Low Latency Communication (URLCC) URLLC is another new service model available in 5G networks. Both the characteristics of reliability, with an error packet rate of 10−5 or less, and end-to-end latencies of about 1 ms serve the different possible new applications such as factory automation, autonomous driving, e-health, building automation, and some specific examples under the broad umbrella of smart cities [50]. Well, to realize such services alongside many others, the current 5G network infrastructure relies on the revolutionary-never-heard-before-concepts of Network Function Virtualization (NFV) [51] and fully applicable end-to-end Network Slicing (NS) [52]. In NFV-based network design, dozens of network services like network address translation, domain name service, and caching are unbound from propriety hardware and undergone soft virtualization.

Virtual World Generation:-It is an imaginary world composed of digital environments with the aid of 3D models, animation, audio, and other virtual interactive elements. These digital items are stored in databases or cloud platforms that are interrogated under the real-world context provided by the AR system. The interrelationship between the real and virtual worlds is managed by rendering and displaying methods. The AR system uses context-aware algorithms to analyze relevant virtual objects for the surroundings of users, and displays them accordingly. The NS strategy allows for multiple logical networks or slices to operate over shared physical infrastructure. Each network slice is allocated dedicated resources for computation and storage, and traffic has to be isolated from the remaining slices, thus providing a true end-to-end virtual network. Physical network resources have been optimised to cater to URLLC services as required by safety-critical applications such as vehicular communications or remote-robotic-surgery with the introduction of NFV and NS. Another evolution in infrastructure to support low-latency communications consists of edge-computing architectures, including Mobile Edge Computing (MEC). In this MEC framework, numerous data-processing assignments are transferred to the cellular base station or other edge nodes with a caching ability, thereby significantly reducing service latency for proximate network users.

c: Massive Machine Type Communication (mMTC) With the advent of the IoT, an extremely high number of low-rate low-power devices require an internet connection. The intermittent communications and small size of payloads facilitate their functions mainly in environmental sensing and utility metering applications. Thus these devices need an mMTC service for internet connectivity. Many components concerning the 5G mMTC service have already been developed in the previous 3GPP releases; however, those requiring URLLC will need the 5G Core network deployment. mMTC can be realized as a flexible combination of NFV and NS whereby automated network functions are made available to it without hampering the cost for mobile service providers. Furthermore, the NOMA scheme in 5G is expected to support mMTC connection by allowing grant-free uplink connections to energy-constrained mMTC devices while keeping the control signaling overhead to a minimum. A promising architecture to support mMTC as well as URLLC services is a collaborative edge-cloud framework that can utilize the benefits of both the cloud-computing and edge-computing towards handling a large amount of data and providing timely feedback to the end-users, respectively.[55]



B. BEYOND 5G: OPEN CHALLENGES AND EMERGING TECHNOLOGIES

The fifth generation networks have brought a variety of new technological innovations, that is, the new design considerations that have arisen in relation to the more severe performance characteristics of the network. Some of these design considerations are covered below and discussed as to how some emerging technologies that might feature in the evolutionary direction of 6G communication networks may address them. a. Throughput: Following the trend of previous generations of mobile networks, the bit/s throughput targets for 6G networks are expected to improve by an order of magnitude from those of 5G. In addition, once the applications of virtual reality become mature, they will require data rates manifold higher than the one promised by 5G. For these reasons, individual user data rates of up to 100 Gbit/s are envisioned for 6G [7]. It is through such high bit-rates that 6G will offer communication channels benefiting from large communication bandwidth traditionally possible in the mmWave elevation between 100 GHz and 300 GHz. Furthermore, large portions of free spectrum have been opened up in the terahertz (THz) frequency band. However, since large propagation losses occur in the communication between these bands, the use of mmWave and THz communications in 6G will mainly be for short-range high bits-rate communications. Moreover, Visible Light Communications (VLC) using data-modulated white light emitting diodes (LEDs) as the transmitters and photo diodes as receivers is another enabling technology that can support extremely high bit-rates in Line-of-Sight (LoS) connections
[57]. Such Gbit/s links become possible since the bandwidth of the optical spectrum is much larger than that of the radio spectrum while also being free to use. Another very promising technology for improving the spectral efficiency of the future wireless networks is full-duplex technology that does concurrent sensing and transmission over the same radio frequency channel or concurrent transmission and reception [58]. b: Network Capacity: Traditionally, it could be said that cell densification has been the main driver in increasing network capacity. However, interference of increased inter-cell to cell-edge users must be managed suitably with respect to reduced cell-size (e.g., tiny-cells). Mounting of smart cities and mobile users on lands and aerial mMTC will all demand, most of the capacity, above and beyond traditional static BSs, such as through cell-densification. This could be remedied partly by bridging cellular networks through UAVs as mobile BSs [59]. These UAV BSs will not only offload the traffic from the static BSs, but they can also relocate dynamically to provide a more favorable propagation channel to the edge users. Moreover, increasing demands in the frequency resource can be addressed through the sharing of mmWave band between satellite and terrestrial communication networks for a more global mobile coverage [60]. This has led to a volumetric description of spectral efficiency requirements into bp by the 3-D immersion in the specifications for 6G coverage.

c: Energy Efficiency

Most of the energy consumption-related operating expenses and carbon emissions of the mobile network can be saved by improving energy efficiency. In this context, energy efficiency approaches for about the deployment and resource allocation of 5G networks are being designed, including technologies like M-MIMO and ultra-dense heterogeneous network that have just come into being. Energy efficiency is considered as the bit rate over the Joule of energy consumed by the particular communication link. Therefore, if 6G networks are aimed at providing more throughput and capacity than what the 5G offer at similar transmission power levels, then an equal amount of increase in the energy efficiency of 6G must be there as that of 5G. One promising way to achieve this objective is through the use of programmable smart surfaces comprising reconfigurable planar meta-materials. These surfaces can be used to coat walls or other structures and then programmed for the desired interaction with impinging electromagnetic waves to provide beam-steering for Signal-to-Noise Ratio (SNR) maximisation or radiation absorption to reduce interference etc. The ML algorithms can be exploited to learn the wireless environment and form the appropriate configurations for desired objectives. Also, for conserving device battery life and for powering UAV BSs for uninterrupted operation, the paradigm of wireless power transfer, energy harvesting, and simultaneous wireless information and power transfer may also feature prominently in the 6G standardisation efforts.

d: Backhaul and Access Network Congestion

Low latency access networks with optical backhaul traffic will be essential for supporting high data rates and very advanced quality-of-service standards pertaining to 6G frontal communication. Part of the solution for backhaul congestion would incorporate the use of storage and computation resources through the front edge nodes of the MEC architecture to provide low latency service to the proximal users of the node. To avoid backhaul congestion, proactive content caching using machine learning at the edge node may further reduce service latency. In addition, wireless optical communications in the visible spectrum could be considered as a backhaul for indoor situations. For outdoor situations, mmWave communications with low earth orbit satellites may provide backhaul services to the static and mobile UAV base stations. In addition to congestion in the backhaul networks, congestion in Random Access Networks (RAN) is another challenge that needs to be addressed in upcoming ultra-dense wireless networks. For example, RAN congestion in ultra-dense IoT networks may occur due to many short-packet transmissions, heavy signalling overhead per data packet, and incredibly dynamic and sporadic nature of device transmissions. Thus, however, many research directions may benefit the above-mentioned investigation, for example, suitable transmission scheduling, peak traffic minimisation, and access control techniques in access networks for flavour of beyond 5G capacities.

e: Data Security

Highly sensitive information concerning users is circulated and stored in mobile networks in the form of geo-tagged , both voice and text messages, and activity logs of mobile applications. The utmost importance is to secure this data from eavesdropping and unauthenticated use. To protect the communication links for 6G, physical-layer security schemes [71] may combine with traditional cryptographic schemes. Also, some promising pathways include cybersecurity schemes based on ML [72] and quantum encryption [73] that could be studied to secure communication links in upcoming 6G networks. The above discussions also suggest 6G communications would incorporate great learning ability across multiple layers of the network to perform diverse tasks, to mention, network management, radio resource allocation, data security, and manipulation of smart surfaces.

III. MACHINE LEARNING FOR COMMUNICATIONS

Conventional applications of ML justify its use in those situations wherein there is no adequate mathematical model of the system, huge amounts of training data are available, the system/model under study is stationary i.e. (slowly varying) with time, and the numerical analysis is acceptable. Lately, the machine learning techniques have gained interest for proffering data-driven solutions for many challenging problems in communication systems. The ML deployment in communications is raring to go, particularly in building self-sustaining and adaptive networks that can fulfill the dynamic reconfigurability demands of the futures devices and services. Ill-placed Data acquisition, with enormous amounts of data and computational power, shall aid in replacing classical algorithmic treatment through mathematical mode conversion through superior computational intelligence, i.e. ML. The next section gives a brief review of the essence of ML, following which one looks into the scope of deploying ML at various layers and ends and types of communication networks.

Feature Overview:

IV. QUANTUM TECHNOLOGY AND QML-ASSISTED COMMUNICATIONS

Here are unusual words that can be found in an untrained context, and the following has not been all about pure learning. QC and ML, on the other hand, serve to create barley in place auxiliary arrangements but for joint benefits in their applicability at communication systems. Parallelism offered by QC continues enacting new disciplines such as "Quantum Information Science," "Quantum Computer Science" [116, 117]. Such parallelism is derived from quantum Physics concept of qubit, entanglement, and superposed conditions. A qubit can simultaneously accommodate both the binary states '0' and '1'; subsequently, any n interacting qubits can simultaneously represent 2n unique binary patterns, which is unlike a single binary pattern at-once in the classical computers. These physical concepts of quantum mechanics are well-known for creating unreproducible patterns of statistical data which could neither occur nor even be effectively executed by classical computers
[41]. The classical machine learning methods have been well established for recognising statistical data attributes in a specific set of data, and also for generating data having the same statistical features (An extensive discussion of classical ML is available in Sec. III). The work of ML implies manipulation and classification of large amount of data in high-dimension vectors; the required time polynomial will be proportional to the data dimension, the parameters of which take very large values. The recognised potential QC is able to very easily handle such large-dimensional data vectors in very large tensor product spaces. One is also expected to see that bringing along both the QC and ML features in a QML conceptual framework may create or identify statistical data patterns which classical computers together with classical ML could not perform very effectively. For the time being, QML is defined to begin developing the use of QC as dimension acceleration for intelligent data analysis methods. However, long-haul predictions would lead to a radically new model of ML for quantum computers. Thus focuses this area around three central sentences: "Why quantum communication?", "What is QML?", and "How can QML play a role in 6G and Beyond communication networks?". A. QUANTUM AND QC-ASSISTED COMMUNICATIONS In this section, we begin with an introduction and the basic principles of quantum communication before looking at the applications of quantum techniques across various sectors of a communications system. We will then highlight the potential enablers of quantum communications along with an associated discussion from existing literature.

1) Fundamentals of Quantum Communications

Various aspects of everyday life will significantly rest on quantum mechanics; from high endurance materials, pharmaceuticals to communications and computing [118]. The putative communication or computing device constituted out of elementary particles must thus follow the axioms of the quantum mechanisms, which are generally analogous to the Euclidean geometry postulates. Having parameters defined in classical physics, operating protocols in communications and computing can be improved using efficient algorithms that exploit quantum physical phenomena in conjunction with quantum principles and tools. Also, quantum techniques provide a prominent avenue for investigation toward finding computationally efficient solutions for classical signal processing problems. With all indications to follow, quantum principles stand to derive very good advantages to the communication networks with increased channel capacity along with the ability to transmit an unknown quantum state, called quantum teleportation, and to securely transmit information through quantum cryptography by means of various advanced communication protocols that will certainly find no recourse in classical techniques [119].

Quantum communication is a newly developed area of activity in the field of telecommunications engineering motivated by the principles of quantum mechanics and the exchange of quantum states [120]. The main research goal of this novel field is to apply the quantum theories/principles to improve the communication systems of the future and to provide additional functionalities. Quantum communications can also be of value for classical communication networks in the areas of estimating the channel, optimising Multi-User Detection (MUD) techniques, designing precoding matrices, and routing through processes with the aid of quantum algorithms [30]. One of the key advantages of the quantum paradigm is its capacity to provide various degrees of freedom. Here, a physical communications channel is replaced with a quantum domain nano-scale object, that is, photons or electrons, considered operationally with respect to two logical values of 0 and 1, as linear combinations of both. For example, with reference to a polarised photon such that P = aPv + bPh where Pv and Ph represent vertical and horizontal polarisation, respectively, values of a and b are then adjusted for optimality of the communication protocols [118]. On the other hand, among the quantum sources, a single-photon source can be considered as an ideal source for generating quantum information, giving pulses whose mean number of pulses is equal to one with zero variance [120]. However, the realisation of such an ideal photon source for practical quantum communications is still extremely problematic, requiring huge amounts of space and skillful technicians. In this matter, alternatives might be adopted for simulating the ideal photon source, including light sources such as faint lasers and four-wave mixing processes for fiber-optic quantum communication systems. Of these, faint lasers would find their application mainly in quantum cryptographic key distribution systems, while four-wave mixing processes would come in handy for optical processing devices like parametric amplifiers and wavelength converters. When quantum communications requirements are needed, the signal can carry information that can be encoded in at least a couple of different ways: by modulating the photons' polarization, which is then detected by single-photon detectors; and by modulating the photons' phase, which is typically measured by homogeny detection [120]. With respect to the first method, since polarization cannot be preserved when quantum signals are transmitted through optical fibers, it is essential to have the means for non-intrusive polarization control to sustain the information being transmitted in the quantum domain. The second approach concerning the photons' phase does not require polarization control; rather, it requires an optical carrier either propagated together with the quantum signal or generated locally at the receiving side to extract the phase information.

Qubit is such a kind of quantum bit or unit that can be described as the quantum version of the classical bit and it is a fundamental point or unit of quantum information in quantum computation and quantum communications. Qubit thus refers to a two-level quantum-mechanical system, such as: up and down spins of an electron, vertical and horizontal polarisation of a photon, etc. Any other orthogonal basis can be employed to represent the state of a Qubit, but the computational basis, which corresponds to the states of |0> and |1>18, is perhaps the most commonly used for that purpose. In this computational basis {| 0>, |1>} the quantum state |φ > of a Qubit system can be expressed as |φ> = a|0> + b|1> , (1) where a, b ∈ C denote the amplitudes of the quantum state in the considered computational basis, and |a|2+|b|2=1. While, when a = 0, b = 1 Young |qi corresponds to the classical bit of 1. When a = 0, b = 1, this equals the classical bit of 0. Conversely, if a = b = 1/21/2, another state of |qi=1/21/2|0i+1/21/2|1i is obtained, which exhibits a symmetry with regard to other states. In fact, for the geometrical representation of the quantum states, 2-D representation and 3-D representation (Bloch sphere) are used to the real-amplitude and complex-amplitude values of the quantum, respectively. An example of a quantum algorithm with real-valued amplitudes is Grover's Quantum Search Algorithm (QSA), Dürr-Høyer QSA, and Boyer-Brassard-Hoyer-Tapp QSA. Some algorithms with quantum counting algorithm and Shor's algorithm utilise complex-valued amplitudes of the quantum states [30].

In this line, authors like the one in [30] have provided their foundations of QC using linear algebra; then, they reviewed all quantum algorithms known today with mention of the application of quantum principles in systems involved in wireless communication. Unlike traditional forms of communication, quantum transmission developed on the uppermost quantum characteristics of information, brings wonderful new challenges and opportunities for the design of new communication protocols for the 6th and beyond. This promises absolute randomness or security compared to classical binary-based communications systems; quite a bit more capacity for information that can be conveyed; and a really significant improvement in transmission quality.

Even better, quantum-based techniques perform tasks remarkably faster and beyond what classical systems can deliver [121]. However, two important challenges still exist in designing new communication protocols in quantum communications. The first challenge deals with their construction because with quantum Internet, there will be a need for quantum switches/routers and repeaters, which becomes challenging because of the no-cloning theorem2).

Applications of Quantum Communications

When it comes to communications, the quantum principles are applicable in every domain such as underwater communications, terrestrial wireless networks and the satellite networks. One of the areas in which quantum communication is highly discussed is e.g. fiber optic communications where the current techniques rely on classical electromagnetic fields and would experience undesired fluctuations when chilled by external noise having quantum-mechanical origins which might limit the performance of photodetectors. Hence the proposed ideal solution is the design of optical communication systems under the quantum-mechanical framework [131]. However, another promising field of application is enhanced security through quantum communication protocols in aquatic scenarios because of the increasing number of vehicles sailing on the ocean surface. Hence, in this respect, the authors in [132] did a feasibility test of QKD protocols in aquatic scenarios and proved the importance of QKD protocols in underwater environments. Also, Satellite Communications (SatCom) are other important areas where quantum techniques can be used for many purposes. For instance, the applicability of QKD protocols in quantum assisted SatCom systems for secure communication between ground stations and the satellite is discussed and analysed by the authors in [126]. Another promising possible application is the quantum Internet, in which it would be possible to transmit Qubits from one quantum computer to another [119]. Furthermore, another area for the application of quantum techniques can be the TeraHertz (THz) communication system currently under research scrutiny all over the scientific community.

Authors in [133] described the properties of THz frequency bands and the major requirements for the implementation of quantum communications in such frequency bands. Another important area of quantum communication is quantum teleportation, in which actual transmission of a particular quantum state involves the quantum devices together with the classical bits, and not the quantum bits, due to the principle of quantum entanglement [128]. The primary challenge in this scenic view is that it involves all wireless setups of quantum teleportation since EPR (named after Einstein, Podolsky, and Rosen) pairs, that is, entangled pairs of qubits, cannot be set up and shared instantaneously by wireless quantum devices. As a result, they cannot distribute EPR pairs to quantum devices through the air. Consequently, it becomes necessary to design new quantum mechanisms capable of performing teleportation from one site to another without requiring a mutual exchange of EPR pairs between the sites. To this end, a novel approach of quantum routing mechanisms by executing quantum circuits in parallel at the intermediate nodes has been recently proposed in [134] and it has been shown that the proposed quantum routing approach is independent of the number of routing hops and is closer to the optimum in terms of time taken to teleport a quantum state.

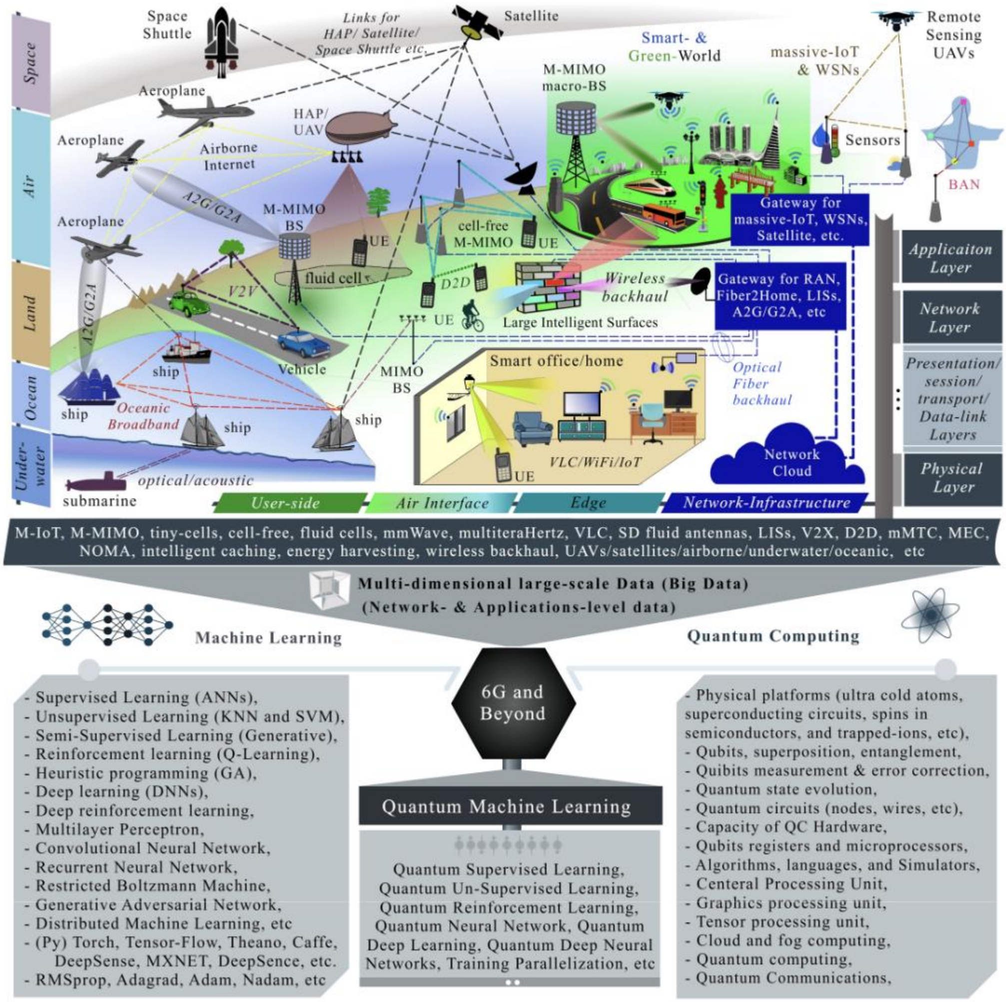
The practical application lays for a quantum annealing chipset that D-Wave has also entered into commerce. Further, the advances in quantum stabilizer codes in recent years for curing decoherence of quantum circuits have also added importance to gate-based architectures consisting of computational blocks with quantum gates. DWave 2000Q3 has a total of 2000 qubits, while IBM Q Experience4 currently holds 20 qubits.

PROPOSED FRAMEWORK FOR 6G NETWORKS AND FUTURE RESEARCH DIRECTIONS

The 5G networks have now entered into the commercialisation phase, which makes it rational to launch a strong effort to draw future vision of the next generation of wireless networks. The increasing size, complexity, services, and performance demands of the communication networks necessitate a deliberation for envisioning new technologies for enabling and harmonising the future heterogeneous networks. An overwhelming interest in AI methods is seen in recent years, which has motivated the provision of essential intelligence to 5G networks. However, this provision is only limited to perform different isolated tasks of optimisation, control, and management nature. The recent success of quantum-assisted and data-driven learning methods in communication networks (discussed in previous sections) has a clear motivation to consider these as enablers of future heterogeneous networks. This section proposes a novel framework for 6G networks, where quantum-assisted ML and QML are proposed as the core enablers along with some promising communication technology innovations. An illustration of the proposed framework is presented in Fig. 4, which indicates various emerging technologies, complex and heterogeneous network structure, multi-space massive connectivity, and a wide range of available big data across different layers, sides, and applications are indicated. The discussion on key thrust areas of future research in the context of the proposed framework is categorised into “Network-Infrastructure and - Edge" and “Air Interface and User-End" sections as detailed in the following.

A. NETWORK-INFRASTRUCTURE AND -EDGE

The extension of conventional land-mobile radio cellular communication networks is toward multi-space highly-mobile radio-to-optic services -oriented cell-free communication networks. Performance standards are envisioned with a future of network connectivity for everybody, anywhere. This integration provides many communication applications multiplied through many-dimensional physical space, for example, underwater (sensors, submarines, etc.), ocean (sensors and ships, etc.), land (indoor and outdoor users, massive-IoT (M-IoT) devices, inter-and intra-vehicle, etc.), air (UAVs, drones, aircraft, high-altitude platforms (HAPs), etc.), space (satellites, space shuttles, space mission robots, etc.), and human body (in-body sensors, brain interface, etc.). An example of the left horizons for provisioning high-performance all-time network connectivity is supplying airborne Internet access to passengers traveling across remote (oceanic) regions in ships and airplanes who will demand the same network service provisions available to the land/home users in a traveling-friendly intelligent world of the future. For enabling harmony across such massively connected complex 6G networks operating in co-existence with its predecessor, tremendous learning and processing capabilities will be required. The various important research directions that will enable intelligent operations at the network-infrastructure and at the network-edge in 6G networks will now be discussed in the following subsections.



1) Intelligent Proactive Caching and Mobile Edge Computing

Intelligent proactive caching or caching the IoT data at all nodes such as the IoT devices and BSs intelligently on the basis of popularity or demand-rate will also benefit the designs of previous generations equally. Although the mechanisms of incorporating intelligence in the nodes to scale popularity for contents have received much acceptance as in, for example, ML advised enhanced caching [198], DL has also been an actively studied literature for processing, classification, and manipulation of contents that will determine their importance in proactive caching at nodes/edge, e.g., DL based caching method in [199, 200]. But to realise this concept of proactive caching, the processing of a very big amount of data to evaluate/estimate most of the media/content popularity becomes necessary. In big data processing context, QC to speed up content/media processing can have a great research potential in proactive caching [30]. Future research could go in the direction of independently and jointly exploring the potential of QC and ML for proactive caching in the emergent big data era.

Predictably shift demands in mobile users exhibit predictable patterns for media/data interest such as the data patterns shift. Intelligently caching such data at serving stations, e.g., BSs, receiving traffic from nearby mobile users is likely to reduce heavy traffic through instant access to popular content straight from the edge of the network while optimising the backhaul of the network. This very promising and emerging concept will also demand new interest with the multiple-access methods, termed Multi-Access Edge Computing, providing real-time access to the radio network and creating room for further joint optimisation of radio resources and data network performance characteristics. Here again, these innovative ideas call for the provision of intelligence and high computation power at the network edge, which are foreseen to take shape in the future as QC, ML, and QML.

2) Quantum Data Representation and Encoding for Communications

In Quantum Machine Learning, data encoding into quantum states is a crucial paradigm governing the performance and efficiency of the algorithms. In their quest to, perhaps some time from now, encode-the real-world signaling in terms of wireless and/or optical communications into qubit states, researchers have had difficulty with the encoding designs. The remaining encoding techniques-amplitude, basis and angle encoding-are to be used to convert classical comm signals into a quantum format. Each of these techniques greatly affects the computational complexity, circuit depth and accuracy of the algorithm. Good quantum encoding enables fast signal processing, noise reduction and dynamic adaptation to changing channel conditions. This could lead to lower latency and improved throughput for real-time communication. Besides, task-specific encoding developments for spectrum sensing, modulation classification, and optimization of multiple-input, multiple-out (MIMO) systems could further boost the incorporation of QML in advanced wireless systems.

3)Bare Hybrid Classical and Quantum Models in Communication Systems These models hybridise classical machine-learning modules, such as preprocessing and feature extraction, with quantum subroutines that perform more sophisticated operations such as classification or optimization. Consequently, a classical system might carry out preprocessing operations to extract features from the signals of a 5G/6G network, whereas quantum support vector machines would manage real-time interference classification. This would allow the benefits of convergence between two paradigms while circumventing the limitations of quantum hardware. Indeed, they are promising implementations in scenarios like edge computing where low-latency processing with high efficiency is necessitated, but where reliance on large-scale quantum systems is not required.

4)QUANTUM REINFORCEMENT LEARNING FOR NETWORK ADAPTATION

It is such a division of QML which manifests quantum advantages in applications involving decision-making in a serialized format. QRL can build adaptive networks in future generation communication environments, where external parameters such as the density of traffic, the quality of the channel, or users' activity change frequently. For example, an agent within QRL could learn routing policies optimized for a quantum communication network or may decide on the most suitable handover strategy between mobile environments. QRL is also suitable for dynamic scenarios because it operates well under conditions of uncertainty and partial observability which is characteristic of wireless communications in vehicular networks, UAV-assisted relaying, and satellites. Via the use of QRL, networks become more autonomous and capable of real time adaptation.

VI. CONCLUSION

This paper presents a review of the emerging technologies in ML, QC, and QML, and introduces a vision for the future framework enabled by QC and QML for beyond 5G wireless networks. Specifically, services to be expected of these advanced 5G telecommunication networks alongside open research issues in B5G communications are thoroughly detailed. The subsequent section is dedicated to a thorough review of the current state in the areas including quantum communication, QC-assisted communication, ML-assisted communication, QC-assisted ML, and QML-assisted communications. A framework for 6G that is proposed by QC-assisted ML and QML communication was given. Discussions of promising new technologies, open research issues, and future research angles were offered in light of the proposed framework. More importantly, diverse possibilities have been explored and put out as enabling technologies for network-infrastructure, network-edge, and air interface, and user-side of the proposed 6G framework. At the network-infrastructure and -edge levels: the role of the proposed framework for intelligent proactive caching, intelligent MEC, multi-objective routing optimization, resource allocation, massive-IoT management, big data analytics, interoperability harmonization, secure links assurance, and data privacy assurance aspects has been discussed and highly recommended. More importantly, for air interface and user-end levels: many enablers for the proposed framework including mmWave communications, teraHz communications, optical communications, VLC, small-and tiny-cells based communications, cell-free communications (UAV BSs and distributed M-MIMO), endto-end autoencoding, learning at user-side, multiple access for massive connectivity, cognitive and self-sustainable radio networks, large scale multi-antenna systems, LISs, and fluidantennas have been discussed in detail with the associated challenges and potential future research directions.

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