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Review

Quantum Communications in Future Networks and Services

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Abstract: Over the last few years, we have witnessed an impressive growth of data traffic and a progressive Digital Transformation of Industry and Society: the deployment of the ultra-broadband and low latency network infrastructures (e.g., 5G) are leading to a global digitalization of several domains. These techno-economic trends are expected to continue and even accelerate in the next decade, at end of which, 6G and smart networks and services will be exploited. Innovation will continue to drive the global economy into the next decade. This paper draws some technology trends and applications scenarios for this horizon, where Quantum Optical Communications are likely to disrupt Information and Communications Technology (ICT) and Telecommunications. Among the enabling technologies and solutions moving in this direction, this paper briefly addresses: quantum optical switching and computing, THz-to-optical conversions and advanced metamaterials for smart radio-optical programmable environments and Artificial Intelligence. The paper concludes with the description of a future application scenario, called Quantum Optical Twin, where the above Quantum Optical Communications technologies are exploited to provide services such as: ultra-massive scale communications for connected spaces and ambient intelligence, holographic telepresence, tactile Internet, new paradigms of brain computer interactions, innovative forms of communications.

Keywords: 5G; 6G; Quantum Communications; Quantum Optical Networks; Quantum Optical Computing; Artificial Intelligence; THz; Smart Radio Environments; Metamaterials; Metasurfaces

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1. Introduction

The deployment of the Fifth Generation (5G) of communications and services infrastructures has already started. Major characteristics of 5G include: the availability of ultra-broadband fixed-mobile connectivity at ultra-low latency, a deep integration of Artificial Intelligence with the network and service platforms, and an increased flexibility and programmability, as enabled by Software Defined Network (SDN) and Network Function Virtualization (NFV). Moreover, 5G leverages the integration of the network infrastructure with Cloud and Edge Computing for enabling services scenarios such as: Internet of things, industry 4.0, augmented/virtual reality, multi-media interactive gaming, unmanned mobility, smart cities, etc.

Recently, the research and innovation activities on the next generation of networks and services infrastructures (e.g., 6G) has been kicked off: deployment target is foreseen as 2030. Innovation will continue to drive the global economy into the next decade.

Over the last few years, we have witnessed an impressive growth of data traffic [1] accompanied by a progressive Digital Transformation of Industry and Society. These trends are expected even to accelerate in the next decade; therefore, future networks and services infrastructures, e.g., 6G, will be facing such traffic challenges in the context of ever-growing network complexity and dynamicity, where very advanced services scenarios are expected (e.g., ultra-massive scale communications for ambient intelligence, holographic telepresence, tactile Internet, new paradigms for brain computer interactions, innovative forms of communications, etc.).

The radio spectrum is to be extended to include millimeter-wave (30–300 GHz) and TeraHertz (THz)-band communications (0.3–10 THz) in order to satisfy the demand for Terabit-per-second (Tbps) links. It should be mentioned that some factors, such as high propagation loss, low power of mm-wave and THz-band transceivers, may limit the distance communication and hence data rates. To overcome these limitations, high-gain directional antenna systems and reconfigurable antenna arrays are being developed (e.g., for massive and ultra-massive Multiple Input Multiple Output systems) but also metasurfaces, which are ideal for smart radio environments [2].

In these future scenarios, the seamless integration of THz systems with optical infrastructures will gain a great importance: as a matter of fact, this integration is coupling the advantages of the radio networks with the unlimited capacity of optical transmission systems. It is likely that 6G, and future networks and services, in general, will leverage novel signal processing systems and methods for direct conversion of data streams between THz and optical domains. For instance, Ref. [3] describes THz-to-optical conversion in wireless communications using an ultra-broadband plasmonic modulator.

On the other hand, we realize also that today electronics is beginning to face physically fundamental limitations (well described by the Moore law) which are posing some concerns about the long-term applicability of current electronics technologies for the next generations infrastructures. It is a common belief that, in the future, electronic technologies will be more and more complemented by Quantum Optics (QO).

QO has been a well-established field of research in physics since the end of the seventies. While in Telecommunications optics has been used mainly for wavelengths transmission with lasers over optical fibers, QO is a clever technique to transport and control optical signals with a greater number of degrees of freedom. In should be mentioned that QO has also influenced observation techniques with multiple telescopes, and it has introduced the anti-bunching properties that are nowadays used to make sure that the system of concern is quantum, or to ensure that one even has a single photon.

As a matter of fact, decades of advances in QO have resulted today in the techno-economic conditions where it is possible to start considering the concrete feasibility of Quantum Optical Communications (QOC) systems.

In general, as shown in Figure 1, QOC are synonymous of applications, such as Quantum Key Distribution (QKD) and super-dense coding [4], capable of exploiting quantum mechanics principles to transport classical, or even quantum, bits of information.

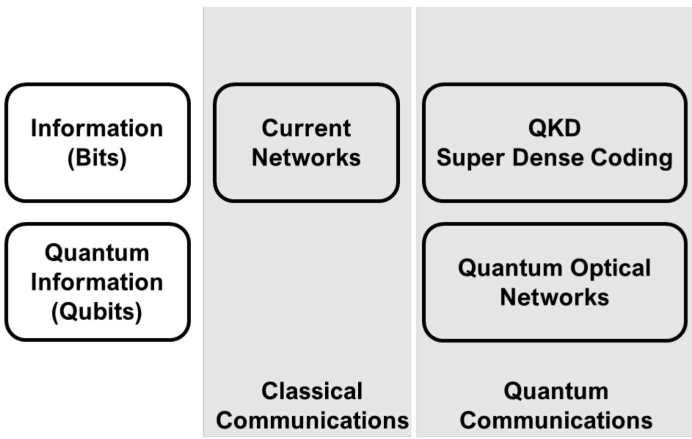

Figure 1. Classical vs. Quantum Communications.

On the other hand, Quantum Optical Networks (QON) extend the concept of QOC, since they can transport, elaborate and store quantum information (qubits).

QON are not simply networks made of Wavelength Division Multiplexing (WDM) systems, add-drop multiplexers and optical cross-connects nodes (which are used for multiplexing/ demultiplexing, extracting and routing different channels of light into an optical network).

QON leverage phenomena with no counterpart in classical networks, such as no-cloning, quantum measurement, entanglement and teleporting, which determine the emergence of new networking and computing capabilities.

At the same time, these phenomena are imposing new and challenging constraints on the design and operations of a QON. In general, QON interconnects quantum nodes and devices for transporting and elaborating quantum information (e.g., in terms of qubits). While a bit encodes one of two mutually exclusive states, at any time, a qubit can stay in a superposition of the two states, i.e., it can be simultaneously zero and one. Therefore, while n classical bits encode only one of 2^n possible states, at a certain time, n qubits can simultaneously encode all the 2^n possible states at the same time.

Remarkably, this creates an exponential speed-up. On the other hand, in QON, differently from in classical optical networks, the no-cloning theorem hinders any uncontrollable inter-switching of an evil observer of quantum information: this prevents quantum information from being transmitted to more than a single destination. Moreover, novel router metrics should be defined, as it is, for example, the entanglement distribution that determines the connectivity of a quantum network for teleporting qubits.

As a matter of fact, photon generation and detection technologies have enormously improved the quality of optical quantum states and the efficiency in handling them; integrated circuits evolved from a basic demonstration of a beam-splitting to massively multimode reconfigurable circuits, and the number of photons simultaneously used is growing [5,6].

An indicative example of an initiative in this avenue is the Innovative Optical and Wireless Network (IOWN) [7] from NTT R&D. IOWN aims to develop an innovative telecom infrastructure that is largely based on all-optical/photonic technology, down to the level of information processing.

In summary, the main contributions of this paper include:

(1) a beyond-5G vision, where QOC, integrated with THz transmission, will set the background for the long-term exploitation of 6G and, in general, future networks and services;
(2) a review of some of the enabling technologies and solutions for turning the above vision into reality, such as: systems for THz-to-optical conversions, quantum access architectures, quantum optical switching and computing, metamaterials for pervasive Artificial Intelligence and smart radio-optical environments;
(3) a proposal of a future application scenario, called Quantum Optical Twin (QOT), where the above technologies are exploited to provide future services.

The paper is structured as follows. After this introduction, section two describes an overview of the very basic principles of QO. The third section provides an overview of technologies and systems enabling QOC. Section four describes a future application scenario.

2. Basic Principles of Quantum Optics

QO can be defined a research and innovation avenue addressing the phenomena (and the related technologies) concerning the interactions between quanta of the electromagnetic field (i.e., photons of light) with matter (i.e., with atoms and molecules) [8]. This avenue includes studying the particle-like properties of photons and demonstrating/testing experimentally some counter-intuitive characteristics of quantum mechanics, such as entanglement and teleportation.

Initial research activities in QO started by focusing on some simple non-classical states of light, like single photons, squeezed states, twin optical beams and Einstein-Podolsky-Rosen (EPR) states, characterized by just a few modes of the electromagnetic field. In a more mature course, QO has addressed quantum states with multiple quantum degrees of freedom (i.e., either spatial, temporal, frequency, or polarization modes) [8]. This has created richer and richer exploitation opportunities for QO, also for the future of ICT and Telecommunications.

As a matter of fact, each mode of the electromagnetic field can be considered as an individual quantum degree of freedom: in fact, depending on the transmission mode, the axis of oscillation in electromagnetic transmission may have different orientations to the direction of transmission.

For instance, in a Transverse Electric (TE) mode, the electric field is transverse to the direction of propagation while the magnetic field is normal to it; in a Transverse Magnetic (TM) mode, the magnetic field is transverse to the direction of propagation while the electric field is normal to it; in a Transverse Electric and Magnetic (TEM) mode, both the electric field and the magnetic field (always perpendicular to one another in free space) are transverse to a direction of travel.

Different sets of modes open the possibility of considering the same quantum state from different perspectives: a given state can be entangled on one basis and factorized on another one. Therefore, it is possible, using the techniques of nonlinear optics, to tailor quantum fields not only in choosing the modes that participate, but also optimizing their spatial-temporal shapes. In other words, the qubits can be encoded into a photon's degrees of freedom, e.g., its polarization (Figure 2), which is the direction of the electric field oscillations.

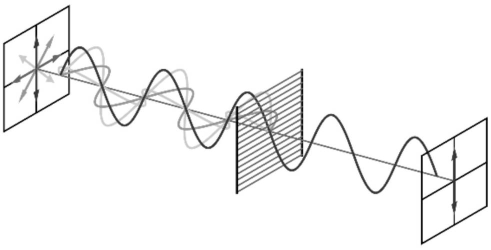

Figure 2. Example of polarization of light.

Moreover, the orbital angular momentum (OAM) of light (Figure 3) has been considered a promising further degree of freedom for multiplexing data in free space and optical fibers and at the nanoscale. OAM represents the component of angular momentum of a light beam that is dependent on the field spatial distribution, and not on the polarization. It has been shown that OAM can be used in the low frequency radio domain and is not restricted to the optical frequency range [9].

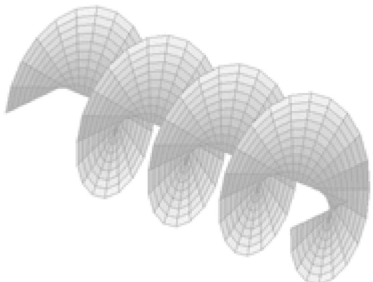

Figure 3. Example of Orbital Angular Momentum (OAM) of light.

For instance, Ref. [10] describes a recently developed air-core fiber that supports OAM modes. High-fidelity distribution of the entangled states is demonstrated by performing quantum state tomography in the polarization-OAM Hilbert space after fiber propagation and by violations of Bell inequalities and multipartite entanglement tests. This is very interesting, as it opens the way to quantum applications where correlated complex states can be transmitted by exploiting the vectorial nature of light.

A detailed analysis of these properties of electromagnetic quanta is outside the scope of this paper. See Ref. [11] for a general review on the state-of-the-art about the generation, propagation, and measurement of high-dimensional quantum states, highlighting their advantages, issues, and future perspectives.

In general, QO is opening wide perspectives for treating complex quantum states with the scope of developing highly innovative infrastructures for networking, processing and storing optical information at the quantum level. The interference between photons produced by independent sources lies at the heart of various quantum operations, becoming essential for the realization of QOC.

In fact, this is necessary for developing quantum teleportation and entanglement swapping that are the fundamental functionalities for developing quantum switching and routing [12]. On the other hand, it is known that the achievable distance for quantum communication links is mainly limited by the employed single photon detectors. Already in 2006, entanglement-based quantum communication reached 144 km [13]. To extend this distance, photon amplification, as used in standard telecommunication networks by multiplying the number of photons, is not possible; in fact, for the no-cloning theorem, copying, or cloning, an unknown qubit with perfect fidelity is impossible according to the principles of quantum physics. Quantum teleportation and entanglement swapping could provide a means towards extending said distances of quantum communication links.

3. Quantum Optical Communications (QOC)

Quantum Optical Communications leverages on the idea of using photons, the quanta of the electromagnetic field, as flying qubits, which have the scope to transport qubits from a physical quantum emitter—through the network for conveying quantum information—to a physical quantum receiver (Figure 4).

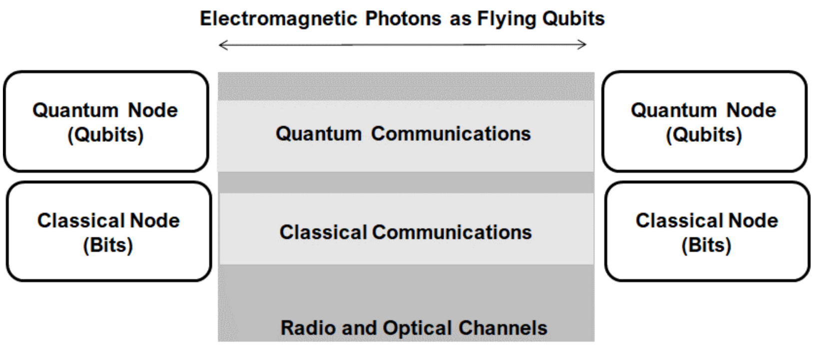

Figure 4. Exchanging "flying qubits" from quantum emitters to quantum receivers.

The advantages of using photons as flying qubits include: weak interaction with the environment (thus reducing the risk of decoherence), control with standard optical components, high-speed low-loss transmissions through optical and radio channels.

QKD [14] has been mentioned as an example of application of quantum-safe cryptography based on the sharing of a security key composed of classical bits.

The principle of operation of QKD is straightforward: two parties (Alice and Bob) use single photons that are randomly polarized to states representing ones and zeroes to transmit a series of random number sequences [15] that are used as cryptographic keys. Alice's and Bob's stations are linked together with both a quantum and a classical channel. Alice generates a random stream of qubits that are sent to Bob. The potential presence of an eavesdropper is revealed by an imperfect correlation between the two lists of bits obtained after the transmission of the keys between the emitter and the receiver.

Technology Readiness Level (TRL) [16] of QKD is around 6 or 7, depending on the maturity of implementations. For instance, there are several projects testing QKD solutions; just to mention a few of them: the European Projects OpenQKD [17], CIVIQ [18], SOCOQC [19], and other ongoing experiments in the Quantum Italian Backbone [20] in UK [21], in China [22], and in Korea [23].

Moreover, we should consider that QKD can operate in the THz regime as well. For instance, [24] provides some examples of the physical hardware and architecture that could be used to realize a QKD scheme in the THz domain.

The next sub-sections will provide some examples of promising enabling technologies and systems for developing Quantum Optical Communications in 6G and future networks and services.

Among them: THz-to-optical conversions, systems for quantum access architectures, quantum optical switching, metasurfaces for smart radio-optical environments.

3.1. Example of THz-to-Optical Conversions

With the growing demand for bandwidth, THz communication systems are expected to become increasingly important. In scenarios, seamless integration of THz systems with QON will gain a great importance as complementing the advantages of the radio networks with, in principle, unlimited capacity of optical transmission systems. This integration requires novel signal processing systems and methods for direct conversion of data streams between THz and optical domains. Quantum technologies (e.g., based on plasmonics modulators) could help in this direction. As an example, Ref. [3] reported a first demonstration of a wireless link that was seamlessly integrated into a photonic network, complementing direct Optical/THz conversion at the THz Transmitter by direct THz/Optical conversion at the THz Receiver. The wireless link operates at a carrier frequency of 0.2885 THz with a maximum line rate of 50 Gbit/s and bridges a distance of 16 m. The THz signal is generated by Optical/THz conversion in a UTC photodiode. At the receiver, the THz signal is converted to the optical domain by using an ultra-broadband plasmonic-organic hybrid modulator.

3.2. Examples of Quantum Access Network Architectures

Quantum optical technologies may find promising exploitation also in the access networks of Telecommunications infrastructures. Ref. [25] provides an example of architecture for a quantum access network performing multiuser QKD over a 1×64 passive optical splitter. In downstream configuration a quantum transmitter is positioned at the network node. The transmitted quantum key is randomly directed to one of the quantum receivers by a passive optical beam splitter. Each user needs a single photon detector and the key is distributed randomly. The upstream configuration requires only a single detector at the network node. The quantum transmitters share this detector by ensuring that only photons from one transmitter at a time reach the receiver.

In Ref. [26] there is another interesting example of a quantum access network for peer-to-peer multimedia service between Optical Network Units (ONUs). Specifically, the proposed architecture supports direct quantum and classical ONU–NU communication by using an N:N splitter. QKD between ONU and Optical Line Termination (OLT) can be performed normally and can support up to 64 ONUs due to the reasonable wavelength assignment of different signals.

3.3. Example of Quantum Switching

Quantum particles can propagate simultaneously among multiple space-time trajectories. This opens up the possibility of developing quantum devices called quantum switches, in which the temporal order of the communication channels is controlled by a quantum degree of freedom, represented, for instance, by a control qubit.

Several implementations of the quantum switch have been experimentally realized and tested [27–30], with a control qubit represented by polarization or orbital angular momentum degrees of freedoms.

3.4. Quantum Optical Computing in Artificial Intelligence

It is a general opinion that the tantalizing promise of a market mass deployment of quantum computing systems and services is still far away for several reasons: noise and decoherence problems electronic qubits, need for viable error-corrections techniques, etc.

The use of QO for developing quantum computing systems shorten the horizon of applicability very much, for instance up to the horizons analyzed in this paper. Quantum computing systems based on QO can advance current computing by using photons as information carriers. For instance, Ref. [31] provides some examples of components, including error correction in photonic schemes, optical quantum memories, and algorithms and protocols.

Still in the same direction, LASOLV represents a remarkable example of a computing machine based on photonics technologies developed by NTT. In particular, LASOLV is a Coherent Ising

Machine (CIM) [32], using an Ising model based on photonics technologies for solving combinatorial optimization problems. As a matter of fact, there is a rich body of work describing Ising computing systems realized with trapped atoms, single photons, superconducting circuits, electromechanical modes, nanomagnets and polariton condensates. Another interesting example is reported in Ref. [33], where the authors propose and experimentally demonstrate the use of spatial light modulation for calculating the ground state of an Ising Hamiltonian. The phase matrix on a Spatial Light Modulator (SLM) acts as a lattice of thousands of spins whose interaction is ruled by the constrained optical intensity in the far field and can be programmed by input amplitude modulation. Feedback from the detection plane allows the spatial phase distribution to evolve towards the minimum of the selected spin model.

AI is one of the most promising areas of application of QO computing. It is well known that current AI solutions are quite resources/energy-hungry and still time-consuming. In fact, today Deep Neural Networks (DNN), as with other AI models, still rely on Boolean algebra transistors to do an enormous amount of digital computations over huge data sets. A roadblock is that chipsets electronics technologies aren't getting faster at the same pace as that at which AI software solutions are progressing. There is general consensus that the current energy consuming trend is not sustainable in the long term; a breakthrough is required if the market of AI applications wants to progress following this trend.

We note that in the basic functioning of a DNN, each high-level layer learns increasingly abstract higher-level features, providing a useful, and at times reduced, representation of the features to a lower-level layer. This similarity suggests the possibility that DNN principles are deeply rooted in classical field theory and QO [34,35].

This aspect offers, perhaps, the confirmation that the way to bypass above roadblocks is using QO computing systems which are much faster and much less energy-consuming than current ones. One should consider that DNNs operations are mostly matrix multiplications, and QO circuits [36] can make such operations faster than traditional processing system. QO computing allows any matrix multiplication to be made, regardless of the size, in one CPU clock cycle, while electronic chips take at least a few hundred clock cycles to perform the same operations. Research and innovation activities are already producing concrete results and prototypes. For example, Ref. [37] provides a feasibility study of an all-optical diffractive DNN (D^2NN): the prototype is made of a set of diffractive layers, where each point (equivalent of to a neuron) acts as a secondary source of an electromagnetic wave directed to the following layer. Further examples are reported in Ref. [38].

3.5. Metasurfaces for Smart Radio Environments

Another promising technology that will see exploitations in 6G scenarios concerns the use of metamaterials (MM) in the ICT and Telecommunications domains, for example for developing smart radio environments (both indoor and outdoor).

MM are materials which contain inclusions (e.g., metallic or dielectric of various shapes and dimensions) designed and artificially engineered to manipulate electromagnetic (EM) waves. Examples of inclusions embedded into a host metamaterial include EM scattering element and nano-resonators. These inclusions are located at mutual distance, typically a small fraction of the wavelength: when an EM wave impinges on the MM, the local fields are scattered from inclusions and interfere thus resulting in a change of the initial EM field distribution. These properties are already used for developing smart antenna and EM processing functions [2].

Metasurfaces (MS) are 2D MM. MS are still made of any periodic two-dimensional artificial inclusions whose thickness and periodicity are small compared to the EM wavelength: due their two-dimensional nature MS occupy limited physical space and can exhibit low loss as photon would in plane-normal direction travel through. Remarkably, it is possible to develop MS showing refractive indexes not present in Nature (e.g., near-zero or negative refraction) [39].

It is expected that MS will have several possible applications, such as: radio coverage in areas not well covered by installation of base stations, development of smart radio environments (indoor and outdoor), holographic security applications, mathematical operations [40] or matrix multiplications for artificial intelligence (e.g., with Optical Fourier Transforms) detection and recognition of images, etc.

MS analog computing can be used for making mathematical operations (such as spatial differentiation, integration, or convolution) directly using the profile of an impinging wave as it propagates through these blocks. Two typical approaches are: (i) subwavelength structured meta-screens combined with graded-index waveguides and; (ii) multilayered slabs designed to achieve a desired spatial Green's function.

Some further examples are provided. Ref. [41] demonstrates that quantum algorithms can be solved by using 3D-printed, perforated dielectric structure into which a Gaussian microwave beam is directed. Neuromorphic MS can be also developed [42]; these consist of multiple layers of nanostructures, which are composed of an array of nanoribbons on top of a dielectric substrate. For instance, an object is illuminated by a plane wave and the scattered light then is processed by the neuromorphic metasurface. By changing the sizes of nano-ribbons, the phase and amplitude of the transmitted light after each layer can be modified which leads to strong interference of light waves passing through the MS; the widths of the nano-ribbons are the trainable parameters during the design of the MS.

In Ref. [43] the authors propose the idea of designing MS where the abrupt phase shifts can be used to control the EM fields patterns. This recalls the approach adopted in the design of reconfigurable transmit-array antennas. As mentioned, in fact, MS can be seen as arrays of nano-antennas: by shifting the resonant frequency, through the nanoantenna designs, it is possible to effectively control the amount of the phase shifted in the scattered signal. Ref. [44] describes a prototype of an information metasurface controlled by a field-programmable gate array, which implements the harmonic beam steering via an optimized space-time coding sequence.

These are just a few examples, in summary, it is argued that MS will play key role in the development of future smart radio scenarios for 6G.

The possibility of coating surfaces in building or kiosks with intelligent (AI-based) MS will allow the creation of smart radio environments capable of radio waves propagation by introducing, in a software-controlled way, localized and location-dependent gradient phase shifts onto the signals impinging upon the MS (Figure 5).

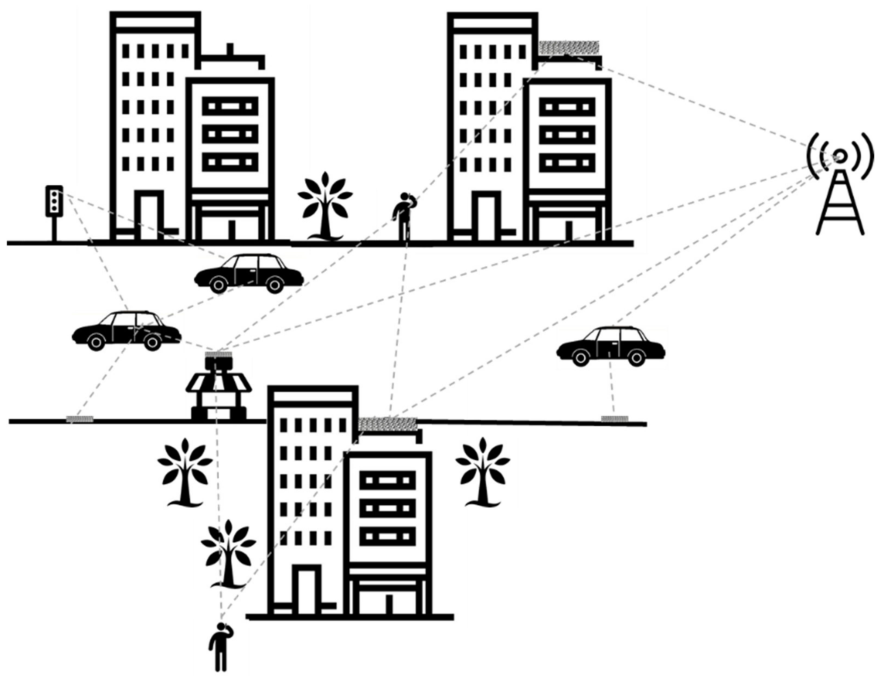

Figure 5. Smart city radio environment (with THz to Optical conversions and metasurfaces).

4. A Future Application Scenario: Optical Quantum Twin

This section describes a future application scenario, called Quantum Optical Twin (QOT), enabled by the exploitation of QO technologies in 6G and future networks and services. QOT could be seen as a long-term extension of the Digital Twin Computing (DTC) vision, towards 2030.

The DTC initiative is part of the IOWN initiative launched by NTT and promoted in Ref. [6]. It is well known that a digital twin is a digital representation of features and characteristics of things, such as machinery, appliances, systems, manufacturing processes or even humans. DTC is a paradigm aiming at expanding the above traditional digital twin concept by extending and enhancing communications and interactions in the cyberspace. For example, the DTC platform consists of the following four layers:

- Cyber/physical interaction layer collecting the physical-world data required to generate a digital twin, and providing feedback to the physical world from the applications;
- Digital twin layer generating and maintaining digital twins by using data received from the Cyber/physical interaction layer;
- Digital world presentation layer providing the framework to invoke digital twin operations using digital twins stored in the Digital twin layer;
- Application layer for developing DTC applications using the digital world presentation layer.

Similarly, QOT leverages four layers, enabled by a progressive exploitation of QOC technologies making it possible to transport, store and elaborate digital and even quantum information.

We could define QOT as a quantum replica of a living or non-living physical entity, which can be used for various applications purposes: quantum replica means that it is developed using QO technologies (even integrating them with traditional digital ones). In other words, the QOT can represent living or non-living physical entity and acting on their behalf in an QO space. A QOT can obviously embed AI capabilities implemented with QO technologies and interact with other QOTs using QOC.

The QOT is different from a classical Digital Twin in the same way as quantum information differs strongly from classical information. While the fundamental unit of classical information is the bit, the basic unit of quantum information is the qubit, which is coded, in QOC, with photons. As mentioned, qubit photons are decoherence-free quantum particles for which photons qubit operations can be performed in an easier way than manipulating electrons qubit in superconducting chipsets.

A future Smart City represents a challenging use case for QOT as the ever-growing level of complexity of modern cities will require solving, in (almost) real time, combinatorial and local-vs.-global optimization problems with multiple constraints. For instance, one can imagine that every smart car equipped with AI systems capable of solving local transportation problems by constantly scanning the smart radio environment (e.g., interacting with sensing MS) to determine the best route for reaching a destination or whether a car should stop or accelerate at the certain intersection. Such local decisions might not be optimal on a larger scale, so the QOT of the Smart City may want to optimize the overall city-wide traffic flows in order to send proposals to the cars' drivers to optimize their travel time or to avoid traffic jams and incidents.

The QOT of a human can be seen as an extension of the state of the art of current virtual assistants, or intelligent personal assistants, and digital twins. It can be seen as a quantum entity capable of abstracting and virtualizing a person and acting on his/her behalf in the quantum space, exploiting quantum Artificial Intelligence capabilities in solving complex problems.

We cannot expect to solve complex optimization problems in real time with classical digital computers for questions of processing time and energy consumptions requirements. This is where quantum computing technologies could make the difference.

For instance, Figure 6 shows two expected approaches for the execution of quantum algorithms workflows: either on gate-model quantum computers or for quantum annealers. In the former case the problem is formulated at a high level and a proper quantum algorithm is selected. Then the quantum algorithm is transformed in a quantum circuit (with gates) which is either executed on a quantum processor or simulated with a quantum computer simulator. In the latter case, the problem is encoded into an Ising-type Hamiltonian, which has to be embedded into a quantum hardware graph. Finally, either a quantum annealer or a classical solver is used.

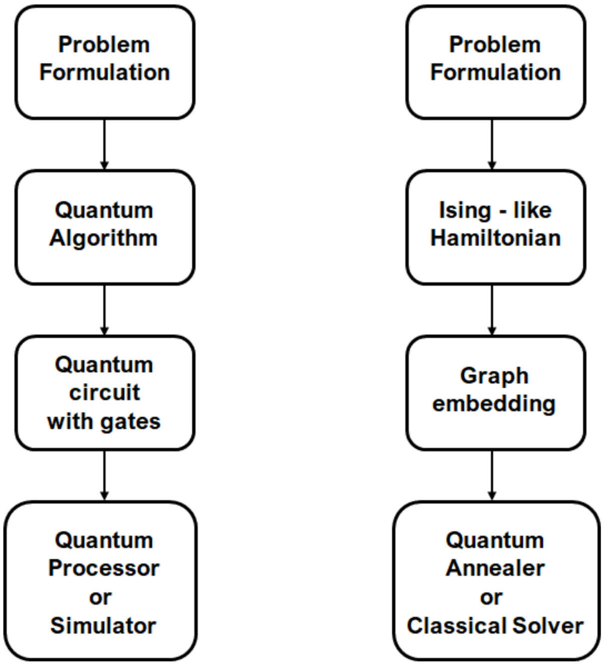

Figure 6. Quantum algorithms workflows: on a gate-model computer (left), on a on a quantum annealer (right).

Concerning the software languages and tools, the scenario is rather fragmented: Ref. [45] provides an overview of open-source software projects and encourages the coalition of larger communities.

5. Conclusions

The deployment of 5G has already been started with the objective of providing a wide variety of innovative services. As a matter of fact, ultra-broadband and low-latency 5G infrastructures are bringing to a global digitalization of Industry and Society. These trends are confirmed and even expected to accelerate in the next decade, at end of which 6G will be exploited.

This work offers a review of some technologies, solutions and applications scenarios where Quantum Optical Communications are expected to disrupt ICT and Telecommunications. Among the key technologies enabling Quantum Optical Networks, the paper briefly addresses: quantum optical switching and computing, THz-to-optical conversions and advanced metamaterials for smart radio-optical programmable environments and Artificial Intelligence.

The paper concludes with an example of a future application scenario, called Quantum Optical Twin, where the above Quantum Optical Communications technologies are exploited to provide services such as: ultra-massive scale communications for connected spaces and ambient intelligence, holographic telepresence, tactile Internet, new paradigms of brain computer interactions, innovative forms of communications, etc.).

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