Towards 6G-enabled URLLCs: Digital Twin, Open RAN, and Semantic Communications

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Abstract—**Recently, the concept of digital twin (DT), open radio access Network (O-RAN) and the adoption of semantic communications (SC) have been labeled as keystone technologies towards the deployment of 6G networks. This paper aims to provide a comprehensive vision of how a DT-enabled and SC based O-RAN architecture can substantially contribute towards the achievement of ultra-reliable low-latency communications (URLLCs) requirements essential for the deployment of the innovative 6G-oriented services. A brief overviews about each single component are primarily provided. Subsequently, potential use cases and services delivered through such unified network framework are illustrated. Challenges and future research directions are also highlighted and discussed.**

Index Terms—**6G, Digital Twin, O-RAN, Semantic communications, URLLCs.**

I. INTRODUCTION

THE rapid and unprecedented development in the areas of wireless sensor networks observed in the last two decades, more specifically in the context of Internet of Things (IoT) and Internet of Vehicles (IoV), as well as the more recent developments and continuous usage of artificial intelligence and machine learning (AI/ML) constantly supported by cloud/edge based computing technology, has contributed and it is still strongly contributing to the huge proliferation and usage of wearable, portable and easy to deploy electronic devices. These trends, in addition to inevitably bring towards the collapse of the current fifth-generation (5G) network — it is envisioned that 5G global mobile subscribers will exceeded 1 billion in 2022, reaching 4.4 billion by 2030 [1] — they are fostering the development of the so called metaverse, an ecosystem based on the principles of global ubiquitous connectivity and pervasive intelligence, which will be able to deliver formidable innovative use cases and services such as tactile internet, extended reality (ER) and autonomous transportation systems. From metaverse vision, it is expected that users' quality of experience (QoE) will be improved by collecting data from physical devices and use it as input for advanced AI/ML mechanisms which provides optimal decision policies. However, in order to realize this innovative vision of data processing for QoE improvement, new challenges need to be addressed. These are pushing towards the development of the new sixth-generation (6G) network standard [2].

The concept of ultra-reliable low-latency communications (URLLCs) has been already introduced during the definition of 5G network architecture. However, 6G-oriented services require even more strict URLLC standards compared to 5G. For example, services like autonomous driving and industrial automation will require communication links with no more than 1 ms end-to-end (E2E) latency and a packet error probability lower than 10^{-7} [3]. As consequence, this is constantly pushing both industry and academia sectors to explore innovative solutions for upgrading the current protocol stack in a way that it results capable of addressing these pressing future requirements [4].

These incessant and increasingly demanding network requirements are constantly exerting pressure on mobile network operators. Specifically, they are persistently seeking new upgrade possibilities for their networks, either by adding new communication equipment or replacing existing ones with other more efficient and flexible [2]. Within the last decade, a similar pressure has been experienced for the development of 4G/5G oriented networks. This brought to the introduction of software defined network (SDN) and network function virtualization (NFV) concepts at the core part of the network, which allowed to meet the necessary network requirements in a very flexible and cost-effective way. But nowadays, the main focus is on improving the radio access network (RAN) part, which approximately accounts for 60%-70% of the estimated network capital expenditures. In order to address this pressing issue of upgrading the RAN components of the networks using cost-effective approaches, both the extensible RAN (xRAN) forum and the C-RAN alliance have proposed different solutions based on the adoption of virtualization principles at the RAN level of the network. However, despite these efforts, the existing virtualization solutions are based on the usage of proprietary interface, making them vendor-locked and then not helpful to alleviate RAN related costs. Driven by these needs of cost reduction and vendor lock elimination, Open RAN (O-RAN) Alliance has been recently founded by global mobile operators, with the main aim of evolving RAN by embedding the concepts of openness and principle of intelligence which will make networks self-driving and autonomous [5].

Another important concept which is also emerging as funda-

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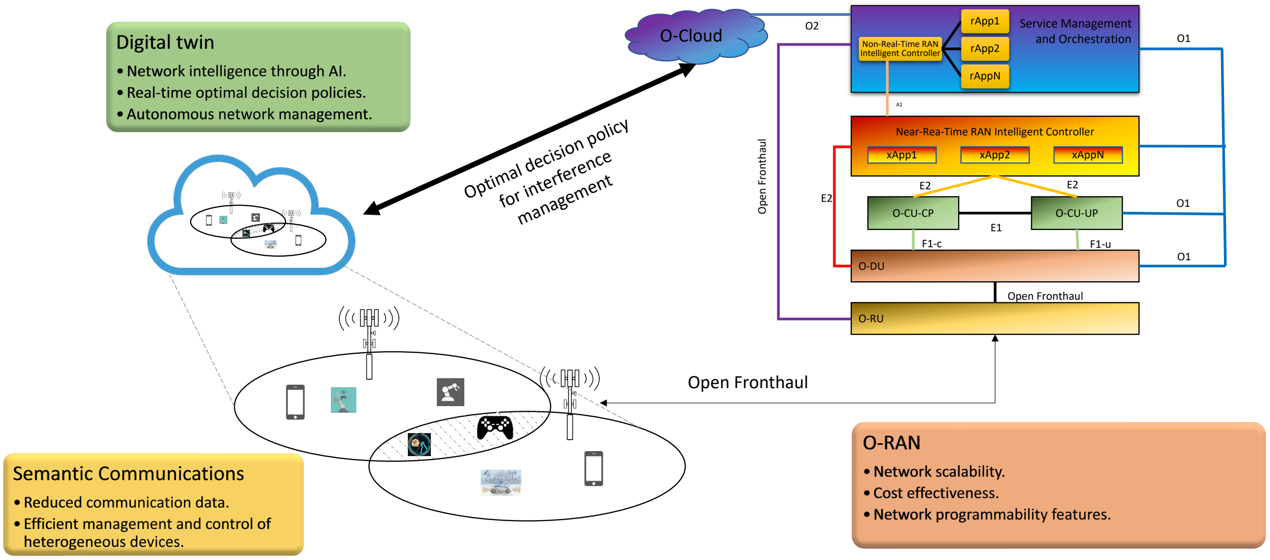

Fig. 1: Synergy among DT, O-RAN and SC toward 6G-enabled URLLCs. This example shows how a DT-enabled and SC-based O-RAN architecture can be used for interference management.

mental keystone towards the realization of 6G infrastructure, is the introduction of the digital twin (DT) concept where every real-world product/system will be digitally represented into cloud/edge servers. Nevertheless, creating a digital representation of a corresponding underlying physical world is only one aspect. The proper innovative aspect of DT is the fact that it will embed artificial intelligence (AI) and big data analytics features. Indeed, by utilizing real-time data coming from real systems as input, a single DT or an entire network of DTs can generate clear and comprehensive models and insights about the behavior of each physical system. This in turn will enable the possibility to perform real-time decision, improving then the development process and efficiency of the entire product/system [6], [7].

The introduction of DT and O-RAN concept will already contribute in pushing forward the current boundaries of 5G network in terms of URLLCs requirements. Indeed, they are strictly interrelated because having a DT of an underlying O-RAN network will be beneficial for continuously optimizing and training the AI/ML models with up-to-date data, thereby improving the intelligence and self-driving behavior of O-RAN itself [8]. However, as its easy to imagine, the creation of a live DT requires the transmission of large volumes of data and the usage of significant computing resources, which can bring to an inefficient utilization of transmission resources potentially blocking the further development of URLLCs based networks. Under these perspectives, the concept of semantic communication (SC) is gaining momentum as additional keystone enabler towards the achievement of high-rate, high-reliability and low-latency requirements of 6G networks [9], [10].

A. *Motivation and Contributions*

In light of what mentioned above, it is clear that a unified network framework embedding O-RAN, DT and SC concepts represent a strong synergism towards the achievement of URLLCs requirements for 6G networks. Indeed, as illustrated in Figure 1, all these components can fully interact and cooperate producing a combined effect greater than the sum of their separate effects. At its core, DT component serves as the central intelligence, providing real-time insights into the network status and device deployment, as well as optimal decision policies for resource allocation, enabling autonomous and efficient network management [6], [7]. On the other hand, SC minimizes data traffic by transmitting the underlying meaning of information rather than raw data. This semantic extraction/reconstruction process relies heavily on contextual understanding, discerning what information is pertinent for senders and receivers alike. With the DT's comprehensive view of the communication context, SC mechanisms can be optimized and refined, leading to further reductions in network latency and superior management of heterogeneous devices [9], [10]. Additionally, the usage of SC for data exchange between DT and its physical counterparts can allow the DT to receive more timely and pertinent information, which in turns allows to provide policies aligned with the stringent requirements of 6G networks. Finally, in addition to offer network scalability and cost effectiveness, the usage of O-RAN based architecture will also offer RAN programmability, meaning that the optimal URLLCs decision policies developed at DT level can be directly and swiftly applied at RAN level. In summary, while there may be some initial challenges in addressing transmission protocol interoperability issues or resource allocation constraints, the potential benefits of merging DT and SC within the O-RAN architecture outweigh the challenges, paving the way for improved network performance and efficiency.

To the best of our knowledge, the current literature lacks overviews that provide a systematic vision of the role of these three innovative technologies in next generation networks.

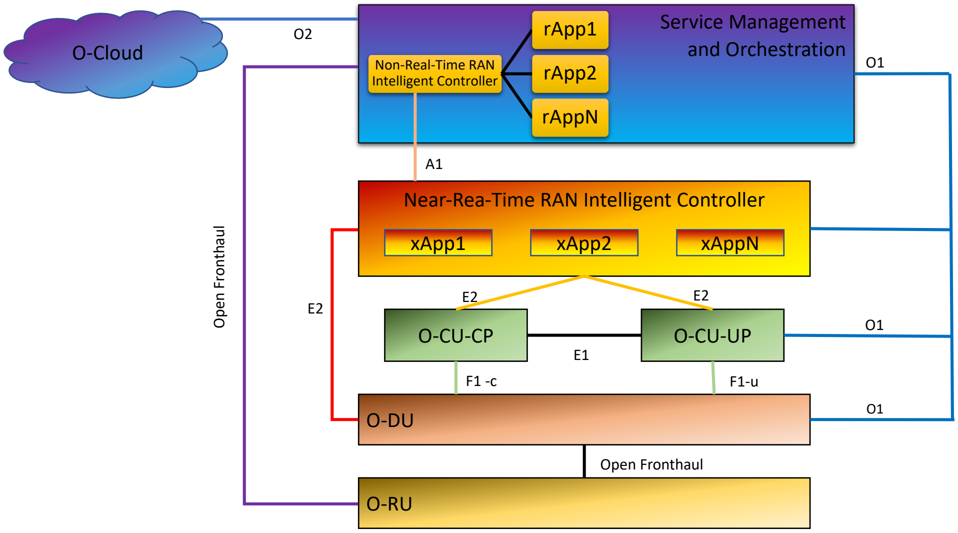

Fig. 2: O-RAN architecture representation.

Under this perspective, this paper provides the following contributions:

- It presents a clear vision on the O-RAN ecosystem with its own principles and features, as well as on DT architecture and SC features.
- The potentialities from the synergy of these technologies as an enabler for 6G-oriented services are illustrated and discussed.
- Open challenges and future research directions on this early stage research area are provided.

The rest of the paper is organized as follow. Brief introductions to O-RAN, DT and SC are provided in sections II, III and IV, respectively. Section V discusses the potential of merging these technologies by illustrating some potential 6G use case that will benefit from such enhanced network architecture in terms of reduced latency and improved reliability. Current challenges and research ahead are provided in section VI. Finally the paper concludes in section VII.

II. O-RAN OVERVIEW

A brief overview about the establishment of the O-RAN concept, as well as an illustration about its reference architecture are provided in this section

A. *The Establishment of the O-RAN Alliance*

Within the last decade, several forums and independent alliances have been established with the main aim of providing an innovative and revolutionary RAN architecture for next generation wireless networks. Even if these types of investigation and innovation activities for RAN component started in 2016, the establishment of O-RAN alliance can be tracked back in 2018 when the extensible RAN (xRAN) forum and the C-RAN Alliance merged together with the scope of promoting an extensible, scalable and software-defined RAN architecture for the next-generation wireless communication systems. To reach these goals, O-RAN alliance is committed to define a new RAN architecture enriched with the concepts of improved intelligence, cloud-scale economies, sharpness, and openness. This will primarily allow for a reduction in capital expenditure and the realization of a more versatile, best-of-breed RAN. Furthermore, the inclusion of artificial intelligent principles will be helpful in managing service requirements for more complex networks, such as 6G [11]. Initially, the O-RAN alliance was founded by five major operators: AT&T, China Mobile, Deutsche Telekom, NTT DOCOMO and Orange. Now, it accounts for more than 300 members among mobile operators, vendors and research & academic institution. Activities are governed by its board of directors composed of five funding members and up to ten elected members. Furthermore, the Executive Committee proposes agendas, priorities, projects, and releases. Decisions and guidance on O-RAN technical topics, as well as approvals of O-RAN, are provided by the Technical Steering Committee (TSC). The O-RAN TSC also supervises the activities conducted by O-RAN Working Groups (WGs). To date date O-RAN accounts up to 11 WGs, each of them dedicated to specific areas of O-RAN architecture.

B. *General Reference Architecture of O-RAN*

As illustrated in Figure 2, the O-RAN reference architecture is composed of different parts, all of them communicating through interfaces conceived in order to result open and inter-operable with standards promoted by either the Third Generation Partnership Project (3GPP) or other complimentary industry standards organizations. This approach has been adopted in order to make possible for operators to select RAN components from different vendors individually. Furthermore, it has been conceived in order to include principles of virtualization aimed at supporting a more efficient slicing splits over the protocol stack. Together, these levels of disaggregation and virtualization will permit to obtain a network RAN architecture with notably reduced costs for network deployment and scaling. Furthermore, the usage of AI-based mechanisms makes

O-RAN component	Functionality
Non-real-time (non-RT) RAN Intelligent Controller (RIC).	Part of the Service Management & Orchestration intended to provide time-sensitive functionalities (xApp) with response time less than 1 s.
Near-real-time (near-RT) RAN Intelligent Controller (RIC).	Part of the Service Management & Orchestration intended to provide functionalities (rApp) with time requirements higher than 1 s.
Multi radio access technology (multi-RAT) control unit (CU) protocol stack.	It is split into Control Plan (CP) and User Plan (UP). This unit hosts radio resource control (RRC) functions, service data adaptation protocol (SDAP) functions, and packet data convergence protocol (PDCP) for both control plane and user plane.
The O-RAN distributed unit (O-DU).	This represents a logical node hosting radio link control (RLC) and medium access control (MAC) protocols as well as high level functionalities of the physical layer, e.g., big fat positive (BFP) compression/decompression for transmission bandwidth reduction.
The O-RAN radio unit (O-RU).	This contains low-PHY layer and RF processing functions, i.e., physical random access channel (PRACH) extraction, fast Fourier transform (FFT), and inverse FFT (iFFT).

TABLE I: Main components of O-RAN architecture.

O-RAN Interface	Description
O1	Used to allow the service management and orchestration (SMO) entity to provide operation and maintenance services to CU, DU, RU and near-RT RIC.
O2	The reference interface between O-Cloud and SMO.
A1	Provide direct communication between non-RT RIC and near-RT RIC in order to transport AI models for the management and optimization of the underlying RAN through the near-RT RIC.
E1	A point-to-point interface between a next generation node B (gNB) CU-CP and a gNB CU-UP that guarantees the separation between transport network layer and radio network layer.
E2	Guarantee connection between the near-RT RIC and underlying CU and DU units.
F1	F1-c and F1-u are logical point-to-point interface between which facilitate inter-connection of a gNB-CU and a gNB-DU supplied by different manufacturers.
Open Fronthaul	Communication between PHY-high (O-DU) functionalities and PHY-Low (O-RU) functionalities.

TABLE II: O-RAN interfaces description.

possible to obtain a self-organizing network architecture. In the O-RAN architecture, the Radio Intelligent Controller (RIC) serves as a crucial component for enabling network intelligence. Essentially, it works as a software-based module housing various applications designed to control and optimize RAN resources. The RIC consists of two main parts, as depicted in Figure 2 and briefly described in Table I . The Near-real-time (near-RT) RIC encompasses different functionalities (rApps) capable of executing network optimization control loops within near real-time intervals (10 ms-1 sec) through the E2 Interface (refer to Table II). Conversely, the Non-real-time (non-RT) RIC, integrated as part of the Service Management and Orchestration (SMO) layer, is tasked with providing intelligent RAN Optimization over longer timeframes (control loops $>$ 1 sec). This dual functionality of the RIC provides a high level of flexibility for enhancing customers' quality of experience (QoE) by ensuring optimal network performance. Furthermore, the RIC facilitates multivendor interoperability and supports the integration of third-party applications. This enables automation and enhancement of RAN operations on a large scale, thereby fostering innovative use cases that reduce the total cost of ownership for mobile operators.

III. Digital Twin overview

This section provides a brief description of the DT concept, illustrating its general architecture and its potential as an enabler of 6G services.

A. *Definition and General Structure*

The concept of DT made its first appearance in 1970 in the context of Apollo 13 mission, used as simulation platform aimed at finding the safest way to bring the Apollo 13 crew back to earth after an oxygen tank accident. In that context, it looked as an integrated multi-physics, multi-scale, probabilistic simulation of a system that used the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin. However, nowadays the concept of DT goes beyond this definition. First of all, the adoption of the DT paradigm requires a continuous and bidirectional exchange of information data between the DT and its physical counterpart. This data coming from the real world, is used at the DT level in order to simulate/emulate the entire life-cycle of its physical twin (PT) as well as its interaction with the surrounding environment. But more importantly, in contrast with the conventional planning and simulation tools used so far, thanks to its AI embedded capabilities a DT is able to provide the optimal decision policy for the sake of system performance optimization [12]. Building on this idea, as illustrated in Fig. 3, it becomes possible to offer a high-level representation of the DT concept by considering the following key layers:

- **Physical asset** which represents the physical world containing, machines, robots and users, as well as all services provided, e.g. industrial IoT, autonomous transportation, telemedicine and so on.
- **Networking asset** containing all the networking used for providing a data flow exchange link between DT and PT. In addition, it supports the exchange of useful information as among DTs located in the surrounding environment.
- **DT virtualization and intelligence** asset having a complete status description about of the real system/product. It mainly consists of storage systems used to store data coming from the real world reflecting PT characteristics and evolution. Furthermore, this layer contains AI-enhanced features used to obtain accurate understanding of the PT and to provide optimal decision policy to improve PT performances.

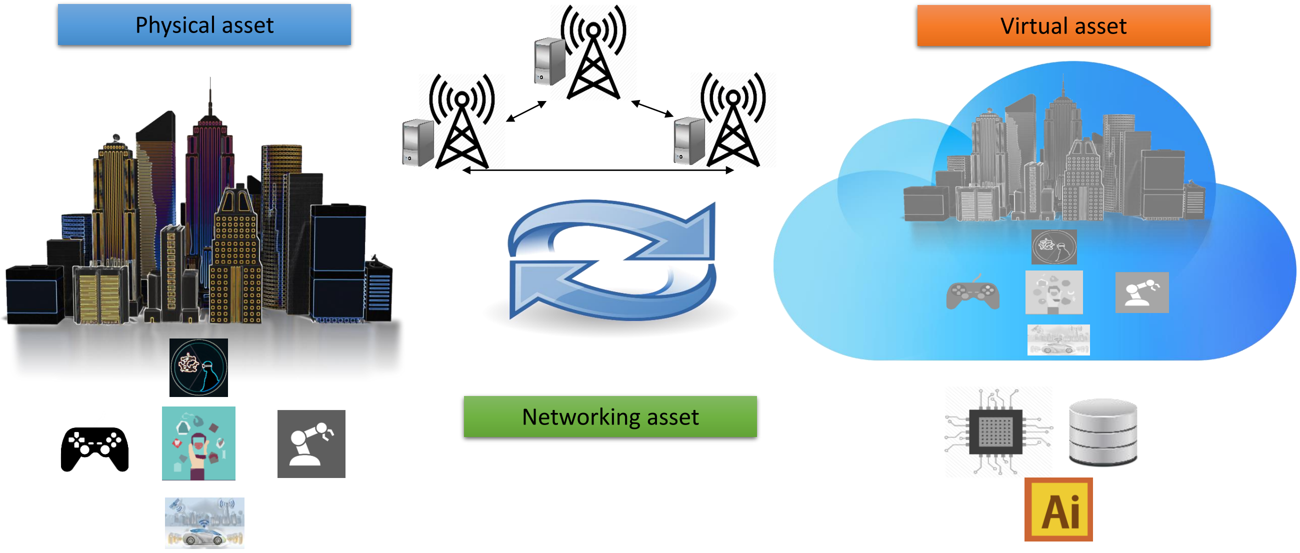

Fig. 3: DT high level representation.

B. *DT as 6G Deployment Accelerator*

Since through the usage of DT is possible to realize optimal decision-making policy for large-scale systems, it can be fully labeled as an enabler for 6G deployment. Indeed, thanks to the usage of AI principles embedded into DT architecture, it will be possible automatically enhance mobile network functionalities with minimal human intervention. More specifically, complex tasks aimed at maximizing network performances such as load balancing, interference management, network planning/configuration and quality of service (QoS) optimization, will be completely AI-driven. This will strongly contribute in creating a smart and self-adaptable 6G network able to learn and adapt itself in order to achieve its predefined KPIs.

IV. SEMANTIC COMMUNICATIONS

A brief introduction to SC and its potentialities in enabling URLLCs in the context of 6G networks is provided within this section.

A. *Brief Introduction*

Within the last fifty years, it has been observed how the evolution of communications technology from the first generation (1G) to 5G has been constantly driven by the need of improving the underlying network in terms of reduced bit-error rate and increased uplink/downlink data rate. These advancements aimed at promoting and facilitating the deployment of even more innovative services such as IoT/IIoT, and IoV, as well as massive machine type communications (mMTC) and enhanced mobile broadband (eMMB). However, in addition to the fact that current communication technologies have nearly approached the Shannon channel capacity limit, it is envisioned that the upcoming advent of 6G will bring substantial changes in the communication paradigm. In fact, it is expected that with the development of metaverse end-users QoE will be influenced by human-centric and computational intensity-related factors, going beyond the purely data-oriented focus of previous network generations. As a result, it will be essential to change approach with respect to the classical information theory (CIT) so far adopted for the development of new communication networks. Indeed, with the massive amount data expected to be generated by new applications, adopting a CIT-based approach would significantly increase the processing latency as well as the reliability of upcoming communication networks. In other words, the adoption of CIT can potentially create a bottleck in achieving URLLCs requirements necessary for the deployment of metaverse-based services. Recently, as response to overcome these potential limitations of CIT, the possibility of switching to SC-based network design principles has been identified as the most valid solution [13].

B. *Principles and Potentialities*

In contrast to traditional communication systems, where the establishment of high data transmission rate with low error rate represents high-priority features, the idea behind semantic communications consists in extracting and transmit only the underlying meaning of the message, which will be subsequently interpreted at the destination. In this way, the SC paradigm will be able to provide:

- reduction of the amount of data required for the deployment of metaverse based services in 6G networks.
- enhanced and efficient management and control of a huge number of devices expected to be deployed within the advent of 6G networks.
- real-time analysis of information extraction from users data with the main aim of maximizing their QoE/QoS.

As illustrated in Fig. 4, a SC-based system can be normally viewed as a three-layer structure. The top layer represent the data source generator providing the information to be transmitted. These data is forwarded to the middle layer representing the semantic channel. This layer is in charge of

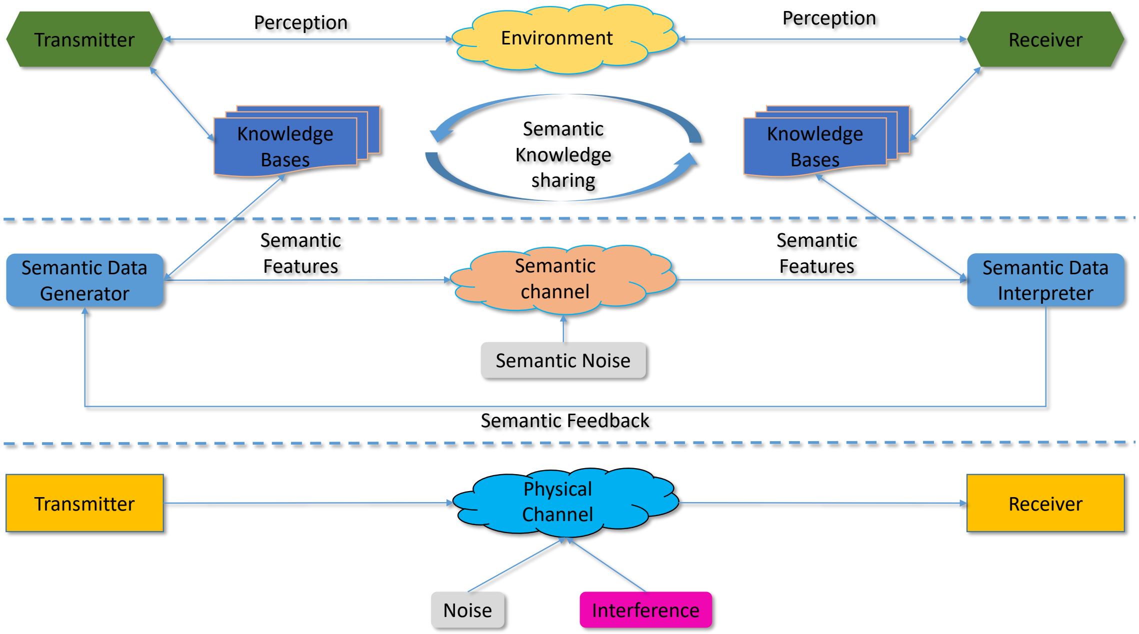

Fig. 4: Representation of a SC system.

performing semantic extraction (SE) operations in order to guarantee that only the essential amount of data is transmitted through the physical channel. This is possible thanks to the usage knowledge bases (KBs) — usually, KBs implementation is based on the usage of deep learning (DL) techniques — used at the transmitter side for SE from the original information flow, and at the receiver side for data interpretation and reconstruction. Due to the ambiguity existing in words, sentences or symbols present in the original message, the interpretation process at the receiver side cannot be considered error-free. Then, as for a conventional communication system, this aspect is modeled through the so called semantic noise [14]. Finally, the bottom layer represent the conventional physical layer where the semantic data will be physically transmitted by using the physical channel containing background noise and interference from other communications. Then, it is envisaged that, compared to the current 5G standard, the adoption of SC will open the way to unprecedented improvements in 6G network performances, such as lower latency and enhanced reliability required for the deployment and metaverse based services.

V. POTENTIAL 6G USE CASES

As already mentioned in Section I-A, based on the discussions and illustrations provided so far, one can notice how a unified network architecture embedding the intelligence of O-RAN and DT, as well as SC principles, represents a promising synergism towards the achievement of URLLCs requirements for 6G networks. By leveraging the intelligence of DT and the efficiency of SC-based transmission protocols within the O-RAN framework, we can achieve substantial improvements in network performance. The DT provides a comprehensive view of the underlying network, enabling the derivation of optimal decision policies to minimize communication latency and enhance reliability. Concurrently, SC-based transmission protocols significantly reduce network congestion and improve spectrum efficiency, further contributing to latency reduction. Moreover, SC facilitates timely and relevant data exchange between the DT and its physical counterparts, empowering the DT to swiftly and easily deploy over the O-RAN components more optimal policies tailored to the unique requirements of 6G networks. This section provides some potential 6G use cases that will benefit from such network architecture in terms of reduced latency and improved reliability.

A. *Metaverse*

The concept of metaverse can be categorized as the most revolutionary concept which is gaining momentum and capturing the attention from both academia and industry. Although there is still not a clear and unified vision about the concept of metaverse itself, the majority of opinions and definitions expressed so far clearly shows a common aspect: it is clearly envisioned that metaverse will have a profound impact on our daily life as well as on the industrial sector. In other words, it will completely reshape the society and its economy. Indeed, metaverse can be either represented as the realization of a new universe or a digital extension of our universe obtainable through the concept of virtual reality and augmented reality, respectively. For this reason, it is reasonable to expect that many of the current technology leaders will provide substantial investments towards its realization; a huge economical revenue is expected from its implementation. However the establishment of more stringent URLLCs requirements represents an essential step toward the deployment of metaverse-based services. For example, VR/AR based applications are expected to have peak data rate around 10 Gbps provided with an end-to-end delay not greater than 10 ms and packet error rate less than 10^{-5} as specified by 3GPP standards. Under these perspectives, the adoption of a unified network framework based on the principles of intelligence of O-RAN and DT and reduced data traffic from the adoption of SC will results very helpful in achieving the necessary upcoming needs in terms of reduced latency and increased reliability. Indeed, from one side the adoption of SC will help in reducing the amount of data to be transmitted per user, avoiding network overloading and providing reduced communication latency. On the other hand, having an AI-enabled DT representation of the environment, as well as the possibility to embed AI intelligence on top of O-RAN architecture, will certainly result to be a very efficient way to find the optimal network resource allocation policy for increased reliability. As result, such innovative network architecture will enable the fulfillment of URLLCs requirements necessary for realizing a metaverse-based environment.

B. *Smart Manufacturing*

Smart manufacturing represents another key scenario envisioned to be delivered within the deployment of 6G networks. It will consists on a complete autonomous interactions between machines. In other words, factories will result more intelligent and energy efficient, as well as more environmentally friendly in terms of interactions with humans. Indeed, for the sake of efficiency in terms of easy factory upgrade, smart manufacturing will be entirely based on the usage of wireless communications, as well as on the support of mobile edge computing for the achievement of a particular task. Then, real-time control and monitoring with URLLCs constraints will become essential features in this particular scenario. Under this perspective, the support of a DT-based intelligence will support the possibility to deploy optimal decision making policies for resource allocation and network management, while openness and cost-effectiveness features provided through the adoption of an O-RAN architecture will foster the possibility of fast and efficient factory expansion. On the other hand, the adoption of SC will contribute in increasing the efficiency of smart factories by providing a more efficient communication way where only the intentions of the control signal are transmitted, i.e. goal-centric communications. This, in addition to reduce the amount of data, will also reduce transmissions errors, resulting in enhanced reliability. More specifically, this aspect of SC is achieved through channel encoding/decoding process where particular types of semantic redundancies are introduced to improve the robustness of communications against physical/semantic interference/noise.

C. *Internet of Things*

The concept of IoT networks will cover an important and essential role in the context of beyond 5G scenario more than ever. Indeed, the continuous and exponential proliferation of various intelligent devices and sensors, like unmanned aerial vehicle (UAV) and VR/AR enabled devices, will bring toward the development of more advanced functions which can be used in different context ranging from entertainment to the management of mission-critical scenarios like post natural disaster. This will bring to a huge increase of data generation and transmission, i.e. consumption of more radio resources. Moreover, time-sensitive services like intelligent monitoring, edge/cloud data processing, and rely-based communications, are expected to be supported by IoT-enabled networks. This means the IoT-based services will require the support of low latency and high accuracy communications [15]. Then, similarly to the industrial scenario, the support of AI principles embedded in the concepts of DT and O-RAN will strongly contribute in providing optimal resource allocations in order to comply with URLLCs requirements. This will be further enhanced by the adoption of SC principles since the amount of data to transmit will be reduced. Furthermore, it is worth to mention that this unified network structure will also contribute to increase the energy efficiency of IoT network, defined as the ratio between the achievable data rate over the power requirements. Indeed, since re-transmission as well as the data amount will be reduced, these will result into a reduction of power requirements at the IoT devices, which is limited in such scenarios.

D. *Intelligent Autonomous Transportation*

Another type of service expected to be enabled within the deployment of 6G networks is the establishment of intelligent transportation systems (ITS). In this context, each vehicle will be equipped with different sensors that provides the possibility to sense and perceive data from the surrounding environment and perform operations like optimal driving trajectory calculation based on traffic flow, as well as collision avoidance and prevention of traffic jams due to accidents. In order to achieve this scenario, it will be necessary to provide URLLCs link between vehicles as well as between vehicles and road side units (RSU) located along the road. Furthermore, the level of interference between vehicles and cellular users might be very high since they will share communication resources. Having a DT representation of this communication scenario will then result helpful in design optimal resource allocation strategies to minimize the co-channel interference. Indeed, thanks to the AI intelligence and data coming from real word, either a DT or a network of DTs can preform data traffic predictions and the generations of all the possible corner scenarios, which can be subsequently used to train offline xApp/rApps of the underlying O-RAN network. In this way, the network will be always ready to perform the optimal resource allocation for particular scenarios, providing then reduced latency and higher reliability. Moreover, the DT will also provide the possibility to train the KBs of the underlying devices, which thanks to the usage of SC will further provide robustness against interference, as well as improved levels of reduced synchronization delay between vehicles communications.

VI. CHALLENGES AND RESEARCH AHEAD

While the combination of DT technology on O-RAN with an underlying SC paradigm holds great promise for meeting the URLLC requirements essential for 6G-oriented services, some challenges and investigations still require particular attention at the time of writing. Most of these challenges, which will be discussed in this section, are associated with the DT concept and the SC paradigm, both of which are still in their infancy stages of development

A. DT Synchronization and Accuracy

One of the main aspects which certainly need attention, especially in the context of DT implementation, is the feasibility of guaranteeing an optimal level of synchronization between the DT and its physical counterpart. Indeed, the advent of 6G-based services will bring even more dynamic environments constantly changing their configuration. Then, having a mismatched digital representation of the environment, such as missing data at the DT from one or more network devices or receiving it at a long delay, could bring the DT to provide the underlying O-RAN network with not optimal decision policies, which can potentially bring to performance degradation of the running system or even worse its failure. For example, having a low fidelity representation of all the involved machinery in Industrial IoT processes can negatively affect the efficiency of the entire production line, as well as, a poor representation of the underlying environment can seriously compromise the perception of KBs essential for the implementation of SC principles. For this reason providing solutions aimed at guaranteeing a real-time synchronization between the physical entities and their DT implementation represents one of the first challenges that need to be addressed. This represents a non-trivial challenge since, in addition to mange the data towards the DT for AI/ML model training, the underlying network will have also to mange a huge amount of data traffic towards edge/cloud servers from IoT devices requesting computing services.

B. Data Management and Protection

In the context of a DT-based system we will assist to the transmission of data from the underlying devices towards their DT. Then, there is the primary issue of protecting data privacy and confidentiality from potential eavesdropper. But other important issues can be identified in this process. First of all, the amount of data received at the DT needs to be pre-processed before being used as input for the training of AI models. To date, this is an operation which needs human intervention. However, in order to make the entire process autonomous and zero-touch it will be necessary the development of novel data annotation mechanisms providing reliable data visualization and processing leading towards accurate training of the models. On the other hand, data from users/sensors towards the DT can be constantly subject to different types of attacks aimed at compromising the optimal decision policy of the underlying systems. Indeed, through data poisoning attack manipulated data will be injected into the legitimate data with the aim of either the corrupting underlying AI logic or to understand the AI logic itself in order intercept the most vulnerable parts of a network and exploit them as malicious nodes. Currently, the most promising approaches are the hone based on the usage of Federated learning, enriched with the principles of homomorphic encryption and differential privacy techniques, and usage of blockchain technology which together will guarantee privacy, confidentiality and protection against logic evasion. Then it will result necessary to fill the current literature gap currently existing in these research fields.

C. SC Models and Implementation

Although he appearance of SC can be tracked back in 1952, only few works on this field have been conducted in literature so far. This means that there is a lack of theoretical research and guidance towards the effective development and implementation of this new type of communication principle, placing the research on SC at its infant stage. Among the open challenges the most relevant are the ones related on SC modelling. For example, there is still a lack of knowledge on how quantifying the capacity of SC channel and how this is related with its inner entropy. Another important aspect which needs attention is the one related on the development of proper semantic similarity metrics used to assess the degree of similarity between different piece of message. In fact, even if several works have been proposed in he context of different fields like, text, image and voice recognition reconstruction, how to measure semantic similarity efficiently and accurately remains still an open problem. Finally, another research directions which need substantial investigation is related on the influence of shared KBs at transmitter and receiver. In particular, to what extent a shared KB influences the communication process, as well as, how to model the semantic flow between partially shared KB still needs further investigations. Last, but not least, most of the current SC based research do not consider the temporal aspect of semantic. This represents an important aspect since the design of KBs must take into account the temporal evolution of the surrounding environment.

D. Security Compliance

The potential implementation of 6G networks based on the network architecture discussed so far, needs to comply with some important aspects. First of all, the DT representation of the underlying network/systems needs to comply with some security aspects. Indeed, DTs will simultaneously perform duties at the planning and management levels of the network by analysing data from the real world and providing optimal settings and network performance in line with the underlying changes. Then there is the need to ensure that security algorithms are uncorrupted and follow the proper security compliance. In this way, it will result necessary to guarantee trust between entities, i.e. DT and the physical counterpart receiving the instructions. On the hand hand, in terms of SC it results essential to guarantee that KBs of transmitters/receivers perfectly synchronized in order to avoid wrong interpretation of messages which can bring to wrong decision that can seriously compromise either the security of users or particular critical systems like military security systems. Last but not least, there are also some security concerns related to the openess of O-RAN interfaces. Indeed, if from one side the openess offers benefits like vendor diversity and cost reduction, on the other hand it can potentially leads towards different types of vulnerabilities such as, data integrity and confidentiality, as well as code injection for unauthorized access and sabotage of network components. Then, robust security measures, such as encryption, authentication, and access controls, in conjunction with the collaboration among stakeholders crucial for ensuring the security and resilience of O-RAN deployments through regular security assessments and audits.

VII. CONCLUSIONS

This paper has presented a comprehensive vision on how, a unified network framework empowered with the concepts of intelligence and openness from DT principles and O-RAN architecture, as well as reduced data flow transmission provided by SC-based mechanisms, can substantially contribute towards the achievement of URLLCs requirements for the delivery of 6G-based services. After summarizing motivation and contributions, it started by providing a brief overview of each element subsequently followed by a discussion on potential 6G use cases that can be possible to deliver through the realization of such DT-enabled and SC based O-RAN network. The paper has been concluded by illustrating challenges and future research direction in this infancy-stage research field.

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