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SURVEY

URLLC in Beyond 5G and 6G Networks: An Interference Management Perspective

MARAJ UDDIN AHMED SIDDIQUI[1], (Graduate Student Member, IEEE), HANAA ABUMARSHOUD[1], (Senior Member, IEEE), LINA BARIAH[2], (Senior Member, IEEE), SAMI MUHAIDAT[3,4], (Senior Member, IEEE), MUHAMMAD ALI IMRAN[1], (Fellow, IEEE), AND LINA MOHJAZI[1], (Senior Member, IEEE)

[1]James Watt School of Engineering, University of Glasgow, G12 8QQ Glasgow, U.K.
[2]Technology Innovation Institute (TII), Abu Dhabi, United Arab Emirates
[3]KU Center for Cyber-Physical Systems, Department of Electrical Engineering and Computer Science, Khalifa University, Abu Dhabi, United Arab Emirates
[4]Department of Systems and Computer Engineering, Carleton University, Ottawa, ON K1S 5B6, Canada

Corresponding author: Sami Muhaidat (muhaidat@ieee.org)

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ABSTRACT Ultra-reliable and low-latency communications (URLLC) is one of the cornerstone services of fifth-generation and beyond (B5G) wireless networks. The URLLC use cases demand strict block error probability and very low-latency targets, and thus even a small 32 byte of payload corruption could be detrimental to the user experience and the overall system performance. Ideally, the current heterogeneous network model and innovative technologies have paved the way for the seamless optimization of B5G URLLC applications. Yet, unprecedented interference issues due to the uncoordinated nature of modern wireless networks, innovative radio access techniques, and frequency reuse methods can significantly affect the performance of the URLLC systems. Therefore, understanding and mitigation of all types of interference associated with each URLLC technology, deployment scenario, and wireless transmission mode are prudent. In this regard, many authors have recently presented interpretative and analytical studies on the management of interference issues; however, the discussion was limited to application-centric approaches and earlier research trends. In this review article, we primarily discuss different types of interference challenges related to the URLLC systems using contemporary designs, frameworks, access modes, and enabling technologies for B5G and sixth-generation (6G) communication networks. We present state-of-the-art research work, in-depth analysis of interference problems, and guidance on the futuristic 6G URLLC technologies and communication networks. This study intends to provide a holistic vision of B5G/6G URLLC systems, their empirical aspects, limitations, essential techniques, and an outlook toward future research avenues.

INDEX TERMS B5G, 6G, eMBB, high-frequency communication, interference, small cells, URLLC, VLC, shared channel.

I. INTRODUCTION

The evolution of the contemporary digital era has witnessed unprecedented technological advancements and is often termed the fourth industrial revolution. The unparalleled and dramatic change in the wireless technology ecosystem is the outcome of hefty emerging data-driven applications, augmented multimedia amenities, novel smart devices, intelligent wearable products, and various machine-type communications [1], [2]. In light of this, lately, international mobile telecommunications (IMT) predictions indicate that global mobile data traffic will increase at an annual growth rate of 55% and is expected to reach 607 EB/month in 2025 and 5016 EB/month in 2030 [3].

Heterogeneous deployments of ultra-dense multi-tier low-power nodes (i.e., femto, pico, micro, relay, remote radio

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head (RRH)) [4], [5] with different service modes (e.g., long term evolution (LTE), WiFi, Device-to-Device communications (D2D)) have been considered as cost and energy-effective (EE) solutions for contemporary wireless communication systems [6]. The basic theme behind the multi-tier architecture is to bring power nodes closer to users and provide content-based services with minimum power dissipation [7].

In a multi-tier heterogeneous network (HetNet) fifth-generation and beyond (B5G) systems, ultra-reliable low-latency communications (URLLC) are one of the prominent new services that demand a reliable channel propagation environment and a high data transfer success probability to satisfy real-time operations. In this regard, active multi-antenna arrays, i.e., massive multiple-input-multiple-output (M-MIMO) [8], [9], and high-frequency communications [10] are considered two principal technologies to achieve the URLLC requirements [11]. The small-aperture multi-antenna offer many spatial degrees-of-freedom (DoF) in which two aspects are directly pertinent for URLLC classes: (i) sustainable signal-to-interference-plus-noise ratio (SINR) links due to high array gain and channel hardening even under the quasi-immune fast fading issue, (2) enhanced spatial multiplexing characteristics with lower latency under multi-antenna multi-user transmission [12]. Although the benefits of M-MIMO are extensively based on the accurate acquisition of channel state information (CSI), either instantaneous or statistical, the landmark achievement is high directivity gain and linear signal processing [13], [14]. Whereas, small-size antenna elements enable the utilization of millimeter-wave (mmWave) and upper spectrum resources which helps in producing pencil-like highly directed beams and support high bandwidth (BW) applications [15].

However, different from the other two-pillar services of fifth-generation (5G)/B5G, i.e., enhanced mobile broadband (eMBB) [16] and massive machine-type communications (mMTC) [17], URLLC is considered the most challenging service due to the stringent low-latency requirements. Precisely, to accomplish real-time instantaneous data requirements for emerging use cases such as immersive virtual reality (VR) [18], telesurgery [19], augmented reality (AR) [20] autonomous cars [21], aerial surveillance [22], and delay-sensitive applications for different types of machine communications, end-to-end (E2E) latencies are identified to have a latency target in the order of milliseconds (ms) [23].

Therefore, to meet the tight URLLC requirements, it is essential to acquire in-depth knowledge of the associated challenges [24]. Accordingly, constraints in URLLC services are further classified into three major lower-layer issues: (i) traffic arrival uncertainty, (ii) channel impairments, and (iii) frequent arbitrary interference problems. The most demanding and inevitable obstacle among all three sub-layer problems is different types of interference [25], [26]. The multi-technology 5G/B5G networks with the random deployment of small cells and frequency reuse method cause severe interference issues. Earlier [27], researchers proved that the removal of only high-intensity interference signals is enough to maintain satisfactory throughput rate performance and quality of experience (QoE) for multimedia services. However, unconventional novel applications have shifted the focus from broadband to strict URLLC division, and thus realization and elimination of all sorts of interference to ground noise level have become crucial [28].

A. INTERFERENCE: AN INEVITABLE IMPEDIMENT IN MODERN WIRELESS NETWORKS

In modern ultra-dense HetNet mobile systems radio-frequency (RF) signals encounter different types of environmental and technical challenges, such as destructive interference, radio resource allocation, user association, frequent handover, high energy consumption, signaling overhead, etc., and become reasons for substandard network performance [29].

To overcome the obstacles following the deployment of the small cells model several resource allocation [30], [31], user association [32], [33], efficient spectrum sharing [34], [35], [36], signal processing [37], energy management [38], and handover protocol [39] schemes in the co-existence of varied services have been presented. In addition, realizing the uncoordinated architecture of 5G HetNet systems and the impact of interference issues, many authors proposed robust interference cancellation and mitigation approaches to minimize the adverse effects on ground noise level [25], [40], [41], [42], and in fact, the empirical analysis also validated the performance in different 5G wireless communication systems. However, the proliferation of intelligent devices and novel use cases has intensified the interference problems and requires a further in-depth analysis of interference issues associated with different B5G and sixth-generation (6G) technology and service classes.

In regard to this, a few researchers have recently highlighted the interference management and mitigation approaches in B5G networks. For example, interference management in HetNet, D2D, ultra-dense networks, and autonomous systems are presented in [43], while a routing-based interference reduction in software-defined networks has been discussed in [44]. Moreover, in article [45], the authors briefly illustrated the key performance indicators (KPIs) of D2D systems and discussed different resource allocation and interference cancellation approaches to optimize the network performance. Herein, it is apparent from the literature studies that authors have analyzed the interference constraints from the outlook of 5G/B5G applications and deployment scenarios. Hence, the crucial discussion on the wireless communication access modes and severity of frequent interference on many envisaged delay-sensitive applications of 6G networks has not been presented. Our study precisely focuses on the interference problems associated with the enabling technologies, innovative applications, and wireless communication techniques of B5G and upcoming 6G URLLC systems. In this survey, we meticulously demonstrate the undiscussed interference issues, for example, inter-slot, inter-slice, inter-service, etc., corresponding to each B5G and 6G URLLC access techniques and services.

B. RELATED WORKS

Recently, many articles have highlighted the design challenges, trends, key enablers, system concepts, and radio resource management for URLLC in B5G/6G networks. For example, in [46] the authors demonstrated the benefits of reconfigurable intelligent surfaces (RIS) technology in 6G URLLC networks and presented case studies on its importance in the co-existence of eMBB/URLLC scenarios. Nonetheless, the examination of overall latency, hardware complexities, and power consumption problems of the RIS-aided URLLC system was not part of the study, and challenges involved in integrated multi-level communication were also left for further exploration. In another study [47], the authors presented a vision of next-generation URLLC networks, coined extreme URLLC, and underpinned by three sub-classes, (i) joint control and communication design, (ii) unaided RF transmission, (iii) and reliable data-driven predictions. The authors broadly demonstrated the opportunities, access technologies, and challenges associated with each of the sub-concepts without investigating the impact of environmental blockages and non-RF-aided propagation characteristics on the performance of URLLC services. Whereas, lately, a critical assessment of the implementation of the 60 GHz spectrum with a variety of multi-access technologies for different delay-sensitive scenarios of industry 4.0 and beyond has been performed in [48]. The investigators also addressed the shortcomings of sub-6 GHz frequency bands, such as spectral congestion, lack of BW resources, and interference issues, without explicitly providing any information on the impact of interference and prospective solutions of the 60 GHz mmWave bands on different B5G/6G services. A review of the contemporary URLLC use cases, specifications, technologies, and prospects of aerial vehicles in the optimization of future URLLC services conferred in [49]. The authors illustrated the importance of distributed edge computing and aerial vehicle systems in the forthcoming URLLC classes, yet the incorporation of artificial intelligence (AI) techniques and robustness in multi-agent learning algorithm designs were not part of the review paper.

Furthermore, spectrum management, collision avoidance, and imperfections of heuristic algorithm designs on shared spectrum resources between diverse service sets are presented in [50], while evaluation of centralized resource allocation and controller design for autonomous cars in the smart city under the constraints of the complex electromagnetic environment has regarded as future research motivation. Focusing on the B5G/6G diversified use cases, the authors [51] classified delay-sensitive scenarios into three sub-classes, i.e., scalable, broadband, and extreme URLLC and proposed two enabling technologies for each URLLC sub-class. However, the significance of new coding and modulation schemes, subcarrier allocation, power consumption, and localization accuracy was inadequately presented, and further in-depth analysis of these essential factors is still demandable to achieve the target trade-offs latency-reliability-throughput performance of delay-critical use cases in B5G/6G networks. Lately, the essence of AI and associated learning frameworks for six new delay-sensitive services, including Holographic radio, enormous Internet-of-Things (IoT) integration, enhanced channel coding, haptic communication, etc., have been briefly explained in [52], and extensive examination of data error probability rate and delay evaluation in different indoor/outdoor environments of each use case is needed to realize the full potential of the future wireless services. Moreover, authors have conducted extensive analysis on the improvement of the multi-level architecture design by using AI-empowered deep learning solutions to meet ultra-reliability and ultra-low-latency (i.e., up to 0.1 ms) challenges of the future wireless applications in [53]. Still, energy harvesting techniques for low-power consumption, development of efficient AI models to further reduce the computing time and algorithm complexities, and blockchain-based technologies for time-critical events are crucial left-over topics in multi-level radio access design that need immediate attention for the agility of future wireless access networks.

C. CONTRIBUTIONS AND ORGANIZATION

It is prominent in recent literature works; authors take a rather application-centric approach to the roadmap of B5G/6G URLLC systems. In addition, the contributions are primarily based on technological trends and emerging applications with a focus on latency/reliability requirements, and the importance of multi-agent learning-based mechanisms. In contrast, in this survey, we provide a holistic vision of the revolutionary technologies, innovative use cases, access methods, and their associated interference issues for the idealistic realization of B5G/6G URLLC wireless networks. Moreover, we also shed light on the future research opportunities derived from contemporary wireless technologies, precisely in accordance with delay-sensitive applications and services. The following points demonstrate our main contributions:

- We provide a comprehensive vision of the trade-offs between throughput-latency-reliability performance and the impact of interference phenomenon in the URLLC ecosystem.
- We discuss modern wireless accessing techniques and their pertinent interference issues, and ongoing research work on the optimization of next-generation cellular communication systems.
- We present an in-depth conceptual overview of resource-sharing schemes, different communication modes, deployment scenarios, and the influence of destructive interference in the coexistence of URLLC and other service sets.
- We also discuss newly introduced high BW URLLC applications, their concurrent strict latency-reliability

demands, and a thorough overview of associated interference challenges.
- The survey offers an outlook toward unexplored possibilities acquired from state-of-the-art technologies as cutting-edge prospective research directions.

To the best of our knowledge, a survey paper discussing the interference problems in employing advanced technologies and potential URLLC classes and serving as a guide toward future research work does not exist in the literature. Table 1 summarizes the research works recently presented in the literature on upcoming URLLC services.

The rest of the article is organized as follows: In Section II, we present the principle and key aspects relevant to URLLC, followed by outlining interference challenges associated with enabling technologies and high BW applications of URLLC in Section III and Section IV, respectively. Section V provides detailed knowledge of resource-sharing schemes and low SINR performance issues on the co-existence of URLLC and eMBB services, along with the recent studies presented in the literature on the optimization of URLLC/eMBB services on a shared channel. Furthermore, Section VI overviews wireless transmission modes and their data error probability performance in interference-limited URLLC small cell networks with relevant studies presented in the literature. Section VII presents an in-depth discussion on high-frequency communication for URLLC, the influence and intensity of interference, pertinent use cases, and related literature works. After that, open issues and future research directions of current and futuristic technologies are presented in Section VIII. Finally, the article is concluded in Section IX. The structure and organization of the paper are illustrated in Fig. 1.

II. URLLC PRINCIPLE AND ASPECTS

The advent of 5G/B5G cellular networks has introduced several new wireless communication use cases, technologies, and deployments trends [54], [55] that create extraordinary challenges in terms of latency, mobility, network's availability, security, and reliability [56]. The authors in [57] summarized the latency requirements along with data rate demands for various 5G/B5G use cases as shown in Table 2. third generation partnership project (3GPP) has conspicuously demonstrated three critical sub-aspects (i.e., latency, reliability, and availability) of time-sensitive scenarios which are discussed in the following sub-sections.

A. LATENCY

The duration of a data packet covering a round-trip over-the-air transmission between two nodes is referred to as latency A data packet can experience diverse types of latency during the propagation over the dedicated channel at distinct phases between the transmitter (Tx) and the receiver (Rx) sides. For example, control plane, user plane, and E2E (constitute of queuing, scheduling, computing, and retransmission (when needed)) latencies.

Since the desirable minimum packet transmission time interval (TTI) for different delay-sensitive cases is in sub-ms [58], the new radio (NR) 5G/B5G air interface uses a short symbol transmission mode (2, 4, or 7 symbols) instead of a legacy long TTI (14 symbols) format to justify the latency requirements [59], [60]. Herein, a realistic study has been conducted on the use of an extremely short preamble composed of only one orthogonal frequency division multiplexing (OFDM) symbol with the aim to minimize the overall latency in the B5G factory automation system, while maintaining packet detection and channel estimation accuracies [61]. The authors asserted that the proposed single preamble ensured performance accuracy up to a 20m distance. Additionally, the transmission estimation process effectively tolerates false alarms caused by non-aligned interfering signals using the same preamble.

B. RELIABILITY

In general, it is defined as the tendency of a wireless transmission medium that can transmit a given amount of data packets within a predetermined time along with extremely low error probability [62]. The minimum packet data error probability in 5G networks is identified as $1-10^{-5}$ percentile of transporting the 32 bytes of a frame within 1 ms [63], [64], while many B5G use cases, such as telesurgery, holographic education, and manufacturing process will strive between $10^{-6} - 10^{-9}$ percentile [65].

Reliability in any system increases with the decrease in the frequent corruption of useful information packets. In the case of URLLC, a typical data value occupies a large slab of the carrier BW and provides enough time-frequency slots for low-rate coding. Unlike turbo and tail bitting convolution codes used in fourth-generation (4G) LTE [66], channel coding in NR 5G uses low-density parity-check (LDPC) codes [67] for the data channels and polar codes for control channels [68], [69]. Exploiting the new channel coding process, researchers observe high coding gain, greater throughput, power efficiency, and very low time delay. Nonetheless, accurate channel estimation and acquisition are susceptible to lengthy delays arising from training sequences interference issues [70], and noticeably short delay is onerous on URLLC performance.

C. AVAILABILITY

The availability of any wireless system can be described as, the actual E2E duration observed by a data packet to deliver the message in line with the agreed quality-of-service (QoS), divided by the system's expected E2E duration covered by the same data packet to deliver the message, in a particular environmental condition.

In other words, any B5G/6G wireless system consider unavailable that does not receive the expected data packet in a specified duration due to transmission constraints such as jitter, fading, blocking, and particularly from interference. Since many modern wireless accessing techniques

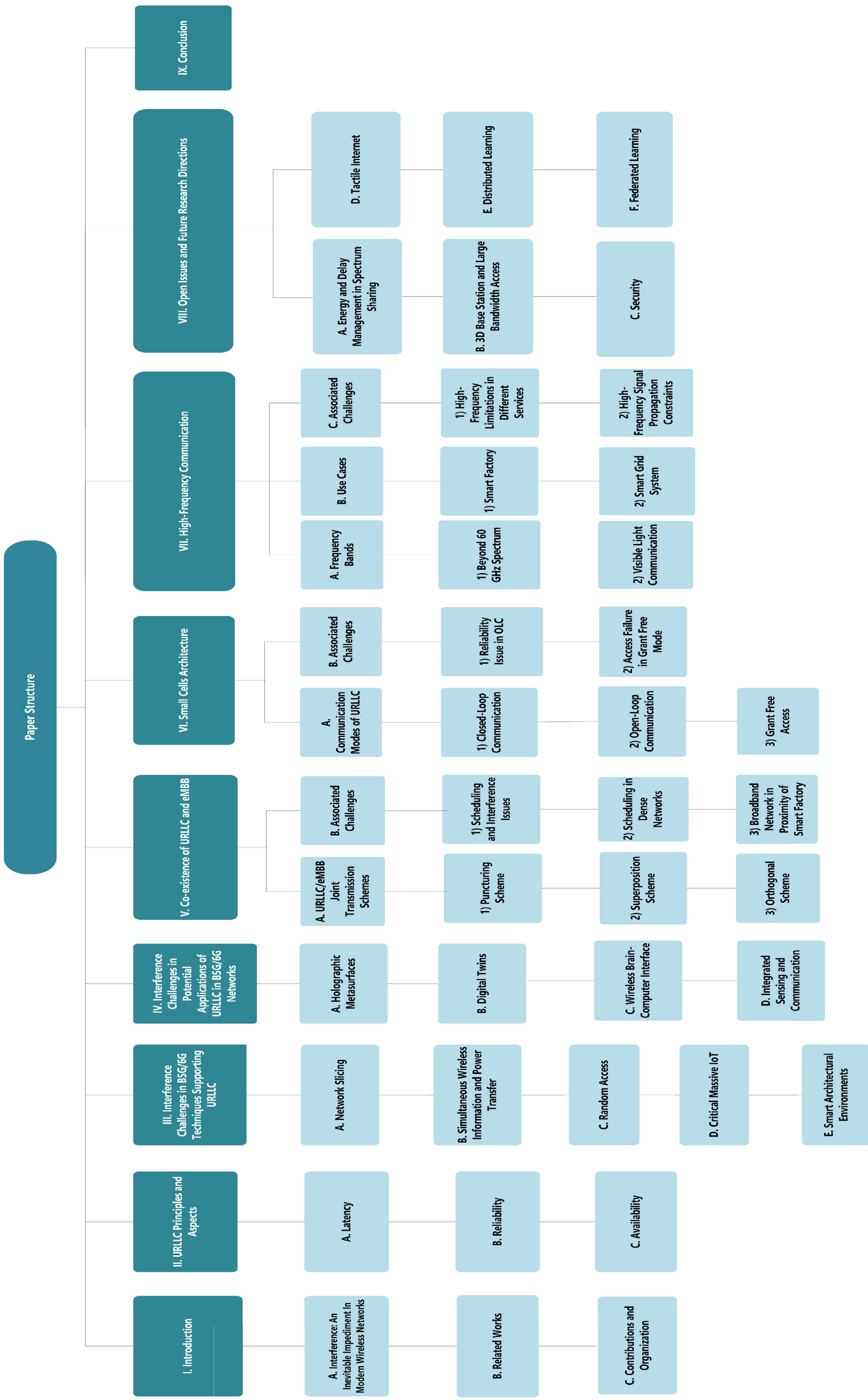

FIGURE 1. Illustrative diagram of the paper structure.

TABLE 1. Summary of recently presented articles on URLLC.

Ref.	Year	Theme	Main Topics	Unstudied Topics
[46]	2022	RIS-aided URLLC in 6G networks	RIS-based URLLC case studies, traffic multiplexing of URLLC and eMBB with smart walls, user association challenges in RIS integrated systems	Energy management and complexities in network operations
[47]	2022	Extreme URLLC applications of 6G networks	Challenges in non-stationary, unpredictable environments for URLLC, non-transmissive and controlled co-designed for delay-sensitive applications	Non-RF-aided propagation characteristics, impact of random device orientation, analysis of user mobility
[48]	2022	Assessment of 60 GHz spectrum in B5G	Wireless standards at 60 GHz spectrum, contemporary antenna models for high-frequency communications, and machine learning (ML) for smart antenna systems	Interference and environmental challenges, dual-band intelligent antenna selection techniques
[49]	2022	Aerial vehicles for URLLC 6G networks	Applications, specifications, and essential requirements of URLLC, importance and challenges of aerial vehicles for upcoming delay-sensitive use cases	AI incorporation and multi-agent learning algorithms
[50]	2021	Spectrum sharing in 5G/6G URLLC	Multiple access, shared channel access, and baseline algorithms for spectrum sharing	AI and multi-agent reinforcement learning algorithms for resource sharing
[51]	2021	B5G URLLC evolution	Novel service classes, enablers of B5G/6G applications, and limitations of 5G-based critical IoT testbed	Applications and challenges of massive connectivity, trade-offs between latency reliability-throughput performance
[52]	2021	AI and deep learning for URLLC	Critical requirements of URLLC for 6G, evolutionary technologies, and AI-based 6G enablers	Network slicing, cloud/edge intelligence, blockchain
[53]	2021	Deep Learning for 6G URLLC challenges	Current research progress, fundamentals and principles of upcoming diverse use cases, and multi-level architecture with AI for the optimization of 6G networks	Limitations of current learning-based schemes, optimization methods, advanced algorithm designs

possess unique interference problems, thus it is important to comprehend the functioning of essential B5G/6G URLLC radio accessing techniques and their associated interference constraints which are discussed in the next section.

III. INTERFERENCE CHALLENGES IN B5G/6G TECHNIQUES SUPPORTING URLLC

A. NETWORK SLICING

Following the advancement in contemporary wireless networks, it has become possible to slice the physical network resources of a radio access network (RAN). The network slicing method has been regulated to efficiently run the set of network functions, using the same network resources by forming a logical setup [71]. The RAN slicing is precisely designed to efficiently handle the scarce radio resources and for slice performance which is relevant to the allocated spectrum access. Herein, the problem of inter-slice isolation is caused when different slices are multiplexed within the same BW resources, and the performance of each slice is affected due to sharing of resources with other slices [72].

Focusing on inter-slice isolation, a binary quadratic non-convex optimization problem is considered in B5G systems. The proposed technique is used to minimize inter-slice interference inflicted by interfering base station (BS) as well as multiplexed slices of numerological order [71]. The authors demonstrated the performance of the proposed scheme by experimentally confirming the high SINR level. However, in paper [73], the authors discussed the co-existence issue of URLLC and eMBB on shared traffic and advocated that URLLC traffic is considered to be much more reliable and has a high decoding probability under the interference of eMBB data traffic. Whereas, to satisfy

TABLE 2. Typical data rate and delay requirements for different mission-critical cases.

Use Cases	Latency	Data rates
Factory Automation	0.25 ms – 10 ms	1 Mbps
Smart Transportation Systems	10 ms – 100 ms	10 - 700 Mbps
Robotics and Telepresence	1 ms	100 Mbps
Virtual Reality	1 ms	1 Gbps
Health Care Management	1 – 10 ms	100 Mbps
Gaming	1 ms	1 Gbps
Smart Grid	1 – 20 ms	10 - 1500 kbps
Education and Culture	5 – 10 ms	1 Gbps

the latency requirements, a max-matching diversity (MMD) algorithm is designed to decode the URLLC data at the BS, while eMBB traffic is transmitted to a cloud server. The simulation results showed superior performance of both URLLC and eMBB services without inter-slicing issues.

B. SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER

In many B5G applications, it is essential that data sharing between several devices must be conducted with high reliability and low-latency level. In such URLLC scenarios, the power and size of intelligent devices remain a challenging requirement, because batteries of low-power devices demand regular power charging to perform critical tasks, and low battery power may degrade its performance [74]. Therefore, simultaneous wireless information and power transfer (SWIPT) technology with finite block length has been realized. The SWIPT technology offers RF energy to be harvested either from opportunistically interfering signals or desired original information signals [75].

Motivated by the SWIPT technology, the hybrid precoding problem has been investigated in a full-duplex (FD) SWIPT interference-limited system [76]. The analysis was performed to optimize the precoding vectors and power splitting ratio that can help in reducing total energy consumption, satisfying energy harvesting constraints, and enhancing decoding capabilities. Meanwhile, the analysis also corroborated that incorporating the structure of strong interference into the decoding of a signal can always support higher rates in comparison to the cases where interference is assumed as noise. Consequently, the authors confirmed the sub-optimal performance of the proposed method and further said that self-interference caused a little performance degradation of a system but can be eliminated by antenna separation technique [77].

C. RANDOM ACCESS

The grant free random access technique provides special DoF to all the users to immediately transmit their symbols without awaiting the resource scheduling from the BS. The instantaneous transmission of users linked to the nearest BS subdues the problems of the scheduling time delay and signaling overhead cost. A well-reputed grant free strategy in a multi-user M-MIMO setting has been performed by assigning a fixed number of, either orthogonal or non-orthogonal, pilot training to all the users [78]. The grant free random access technique commendably supports the latency and reliability of the data packets, either on shared or dedicated, spectrum resources. However, the performance of the technique degrades with the increase in the number of users, also the assignment of unique pilot sequences to each user becomes impracticable.

In contrast, unsourced random access also refers to a variant of grant free random access that allows all users to exploit the same codebook to access wireless links [79]. The codebook technique empowers the BS to decode the list of transmitted messages without any identity knowledge of active users; on the other hand, the superposition coding technique helps in designing the unsourced codebook precisely to avoid multi-user interference issues and minimize the decoding error probability [80]. Thus, contemplating the future massive access of different smart devices, empirical evaluation of unsourced random access coding schemes for fixed frame length and packet loss rate could be performed in a delay-critical scenario for a minimum SINR threshold [81].

D. CRITICAL MASSIVE IoT

The interconnected sensor networks are expected to enable various critical IoT monitoring applications, wherein, orthogonal multiple access (OMA) techniques would not justify the simultaneous access of a large number of IoT connections due to the limitation of spectrum resources [82]. Typically, non-orthogonal multiple access (NOMA) has gained significant attention due to the employment of the superposition coding method and has the potential to achieve massive access with high spectrum efficiency. Simultaneously, employing successive interference cancellation (SIC) technique at the Rx to minimize the probability of co-channel interference due to the non-orthogonal approach. Yet, in the NOMA-based URLLC systems, the decoding error probability increases with the increase in interconnected IoT devices, precisely the reason being the frequent addition of unwanted signals of the neighboring devices [83]. Moreover, the massive number of Internet-based intelligent products increases the computational and algorithmic complexities of SIC Rx and incurs computing-time delays, which is completely unacceptable for delay-sensitive massive IoT networks. To subdue the SIC challenges, a general perspective is to organize IoT devices into different sizes of several clusters and apply the SIC method within each cluster. However, in a multi-cluster scenario, inter-cluster interference does exist and it directly affects the overall latency and reliability of the critical IoT networks.

Lately, a duty-cycling procedure has also been adopted in critical wireless sensing IoT systems, because the nodes can stay in sleep mode while waking up sporadically only at scheduling times [84]. These moments hold the Tx to wait for a certain period of time meanwhile awakening its target node to initiate data exchange. This whole process also has a straightforwardly negative impact on the overall latency and reliability of the large-scale sensor IoT networks. [85].

Furthermore, lately, short packet transmission has gained significant attention for IoT networks due to the development of finite blocklength information theory. Since many B5G URLLC applications demand ultra-low-latency, thus mandate short packet communication. However, the effectiveness of small payload over-interference limited networks, particularly under channel uncertainty has broadly remained unexplored. For instance, the distributed and broadcasting nature of the wireless networks, e.g., machine-to-machine communication, interference is inevitable. Whereas, the impact of interference on the overall performance of the system is also not well studied from the current literature, particularly when MNs are restricted to utilizing codewords of finite blocklength regime. Thus, research work in order to investigate the impact of the interference on the performance of critical IoT URLLC networks under the scenario of bursty arrival of data packets within the short packet communication is much needed.

E. SMART ARCHITECTURAL ENVIRONMENTS

Modern digital cellular networks are experiencing evolution in electromagnetically active surfaces such as man-made walls, boards, roads, and full-stack buildings [86]. The emerging RIS is one of the newly introduced technologies that will utilize the potential of smart surfaces. Fundamentally, RIS consists of many passive reflecting arrays in which each array can generate an independent phase shift on the impinging electromagnetic (EM) signal. Thus, by careful handling of the phase shifts of all reflecting arrays, the reflected EM waves can be easily added with the direct signal from the BS and can enhance the system SINR level. In practical scenarios, RIS can be highly beneficial in extreme delay-sensitive arenas, e.g., factory automation, manufacturing processes, etc. However, in critical industrial settings, RF signals are often blocked due to the widespread deployment of intelligent machines and sensor nodes and can reduce the expected performance metrics [87].

For example, in ultra-dense wireless networks, high-frequency radio signals often suffer from significant path loss due to environmental blockages and the addition of neighboring signals destructively [88]. Thus, to increase the coverage of high-frequency RF signals in B5G/6G networks, the authors analyzed the performance of RIS-aided mmWave communication in a B5G/6G cellular network [89]. The experimental test was performed wherein users received signal power from two separate sources, i.e., from the associated BS as the desired source, and the other from the nearby interfering BSs. The result showed that high SINR gain can be achieved in the presence of co-channel interference by appropriately selecting the number of RIS elements and active antenna nodes at the BSs. Nonetheless, the complexity appended by a large number of RIS and small-size antenna elements can seriously affect the delay performance.

Indeed, due to the broadcast nature of RF signal transmission, different access techniques encounter a variety of environmental and propagation challenges and observe modifications in the wireless signal characteristics. Though most receivers are capable of appropriately decoding the environmentally altered signals, still high decoding errors of modified signals can badly influence the URLLC application performance.

IV. INTERFERENCE CHALLENGES IN POTENTIAL APPLICATIONS of URLLC in B5G/6G NETWORKS

A. HOLOGRAPHIC METASURFACES

Future 6G wireless networks are envisaged to create low-powered, ultra-reliability, and higher data rates transmission ecosystems. Unfortunately, traditional antenna techniques cannot satisfy the expectations due to several reasons including antenna design complexity, a large number of RF chains, high power dissipation, and complex hardware structure [90]. A surface antenna a.k.a reconfigurable holographic metasurfaces (RHS) has emerged as a reliable technology and offers flexibility in transceiver integration, beam steering, and low hardware costs.

For industrial Internet-of-Things (IIoT) networks, reflected arrays and refractive metasurfaces have been considered reliable techniques for wireless communication. Likewise, RHS consists of a large number of meta-material radiation elements and poses an ultra-thin structure compared to intelligent reflecting and refracting surfaces [91]. It has the capabilities to dispense high data rates performance and fulfill low-latency requirements. It is believed that future ultra-dense networks will be highly benefitted from the RHS technology, however under high-frequency communication, the uncoordinated directional transmission of active sensor nodes could be susceptible to high-intensity interference, and further exploration of the associated interference problems and their effective mitigation approaches would enrich the 6G wireless communication environments [92].

B. DIGITAL TWINS

Realizing the growing involvement and benefits of AI, advanced sensing instruments, and radio communication technologies; it will be possible to create an exact replica of devices, machines, systems, physical entities, and even locations, in a virtually developed environment [93]. In 6G networks, the digital replica of any physical entity is coined as a digital twin and by exploiting its properties, users would be able to assess reality in a virtual world. Principally, the fundamental technology of digital twins is the IoT technology that senses and collects real-time multi-source data. It integrates AI and software analysis to develop digital simulation models that can be modified and updated dynamically.

In digital applications of wireless networks, secure and uninterrupted communication always remains a major concern, and the seamless performance of digital twins in multi-hop IoT sensor networks is highly susceptible to interference issues [94]. Likewise, the mmWave and tera-hertz (THz) spectrum are expected to justify the future extreme BW applications, and one of the possible scenarios is to observe and interact with the digital twins, using VR instruments or holographic displays. This inter-communication between users and digital twins could result in instant actions in the physical world and deliver immediate solutions. Yet, the challenging factor is to develop a high-precision digital replica of such as for $1\text{m} \times 1\text{m}$ dimension needs tera-pixel which requires uninterrupted 0.8 Tbps data rates, and the situation would become more challenging when a non-cooperative interference Tx reside in the same vicinity and operate on the same frequency channel causing high interference issues. Since mmWave and THz frequency bands extensively rely on pre-defined beamforming (BF) codebooks and precisely focus on increasing the gain of the user, a non-cooperative interference Tx in the proximity operates on the same radio resources are vulnerable to interference problem [95].

Moreover, with limited battery power and computational resources, the intensive computing assignments generated by the massive IoT devices could not be able to smoothly process all by themselves and thus escalate critical latency targets. Thus, mobile edge computing (MEC) is assumed to be another possible solution that can be helpful in meeting the latency targets of URLLC applications. Such as in MEC-empowered digital twins the IoT-generated tasks can be offloaded to MEC nodes. Since it promptly processes intensive computational acts and reduces offloading processing time. However, the MEC-enabled digital twins' offloading strategy encounters a cochannel interference problem that emerges from the extensive reuse of frequency resources and significantly affects the system offloading performance.

C. WIRELESS BRAIN-COMPUTER INTERFACE

The evolution of wireless brain-computer interface (BCI) will have a significant impact on healthcare sector applications in which humans can govern prosthetic limbs or neighboring computing intelligent products via brain implants. This will revolutionize the modern health monitoring system and introduce new service trends and thus need 6G wireless data connectivity. It will create interaction between user-to-user and user to their environment using discrete smart products and embedded tools in the world around them. Currently, the integrated BCI is constructed with effective dry electrodes technology as it can provide benefits of high fidelity signals and convenient installation [96].

Meanwhile, several research studies have been performed on the development of smart dry electrodes, and electroencephalography (EEG)-based wireless BCI systems are considered an efficient tool to provide a highly reliable link between the brain and external smart devices, nonetheless EEG-based systems commonly suffered from physiological interference and power-line noise. The physiological signals can have amplitude 50^{-6} volt and up to 30^{-3} volt while the amplitude of EEG-based BCI signals are relatively $10 \sim 100^{-6}$ volts [97] and it has a direct impact on the seamless link reliability between brain and computing system of the BCI systems.

D. INTEGRATED SENSING AND COMMUNICATION

Initially, integrated sensing and communication (ISAC) systems were considered two disparate entities and designed separately while using different frequency bands [98]. Owing to the pervasiveness and high resolution in time and angular domain of M-MIMO with high-frequency communication paves the way to enable ultra-high-accuracy sensing via radio links. Fundamentally, physical (information processing, channel characteristics) and hardware properties in the amalgamation of mmWave or THz spectrum with multi-antenna streams, depict striking similarities between radio communication and sensing systems [99]. As a consequence, it is prudent to integrate sensing and communication using the same frequency channel and hardware structure to ameliorate spectral efficiency (SE) and minimize hardware costs. Even so, sharing of the same frequency resources in a cooperative sensing network considerably proliferates the interference problem. For example, a few authors [100] investigated the performance of NOMA in the ISAC system in the presence of inter-user interference. The authors proposed a NOMA-based multi-antenna integrated sensing and communication technique to mitigate the interference problem, and though simulation results confirmed the satisfactory performance of the proposed framework, robust interference cancellation approaches are still demandable to eliminate the adverse effects of interference to a ground baseline level and justify the extreme reliability and very low-latency targets of diverse ISAC use cases, such as automobile sensing for car drivers and passengers, surgery with cooperative humanoid, touchless home appliances, etc.

Likewise, in-band FD mode is a fundamental technology in a ISAC wireless system but it encounters intrinsic interference problems. Realistically, in-band FD mode exploits the same radio channel for simultaneous two-way communication and supports efficient utilization of the radio spectrum, unfortunately, the strength of the received signals is commonly 100 dB lower than the transmitted signals and this eventually becomes the reason for cumulative signal interference in ISAC networks. This cumulative interference increases frequent decoding error issues and instantly reduces data rates, latency, and secrecy capacity performances. Therefore, agile and concrete approaches to precisely eliminate the cumulative interference impediment are indispensable in ISAC wireless networks.

It is evident that future wireless networks would support a plethora of diverse wireless communication services, and indeed the simultaneous operation of delay-sensitive and broadband user/machine services in proximity may badly affect by interference. In this regard, many authors have recently proposed robust joint transmission schemes in the literature on the co-existence of URLLC and eMBB traffic to satisfy the ultra-reliability and very low-latency of URLLC applications whilst throughput requirements of eMBB services. Some of the agile techniques present in the literature that can satisfy the requirements of both URLLC and broadband services are discussed in the next section.

V. CO-EXISTENCE OF URLLC AND eMBB

With the scarcity of spectrum resources in the centimeter-wave band, both eMBB and URLLC traffic shall reside on the same carrier. Thus, achieving greater SE for eMBB and a very low-latency for URLLC traffic becomes a challenging scheduling task owing to the intrinsic trade-offs between SE, reliability, and latency [101]. Indeed, to maintain strict URLLC requirements, communication should be efficiently engineered to completely avoid the interruptions of data packets. This can be made possible by setting a tight block error rate (BLER) to achieve the required URLLC SINR level. Nevertheless, the co-existence of eMBB and URLLC services have a high expectancy of packet data corruption due to inter-service interference (as shown in Fig. 2). Orthogonal methods are typically assumed in order to mitigate the destructive interference, where frequency resources of one wireless scheme are isolated from the others. In this regard, URLLC traffic is always scheduled over the eMBB traffic for its delay requirements.

For efficient spectrum manipulation, the time division duplexing (TDD) method is considered the most effective technique of RF packet transmission over multi-antenna streams, especially for URLLC classes. The authors in [102] have constructed a list of probabilities of different inter-network interference cases using TDD synchronized and unsynchronized mechanisms that are presented in Table 3.

TABLE 3. Probabilities of inter-network interference cases.

Transmission link	Synchronized TDD		Unsynchronized TDD	
	From eMBB to URLLC	From URLLC to eMBB	From eMBB to URLLC	From URLLC to eMBB
DL-to-DL (BS-UE)	50%	50%	37.5%	37.5%
DL-to-UL (BS-BS)	0%	0%	37.5%	12.5%
UL-to-UL (UE-BS)	50%	50%	12.5%	12.5%
UL-to-UL (UE-UE)	0%	0%	12.5%	37.5%

A. URLLC/eMBB JOINT TRANSMISSION SCHEMES

Some of the resource allocation and interference isolation schemes on the shared channel for URLLC and eMBB traffic presented in the literature are discussed below.

1) PUNCTURING SCHEME

Recently, the improvements in the air interface of NR B5G networks has escalated the support for shared URLLC and eMBB traffic. Due to the strict latency requirement of URLLC cases, the 3GPP standardization authority proposed that URLLC traffic will be served in short symbol TTIs (i.e., 2, 4, or 7) by puncturing the resources of ongoing eMBB service. Specifically, the 5G BS immediately interrupts eMBB ongoing transmission during the sporadic URLLC traffic in order to meet the latency requirement. In this situation, the protocol serves the delay-critical traffic efficiently at the cost of performance degradation in eMBB traffic [103]. In addition, offering priority to URLLC traffic may damage the proportional traffic fairness among the eMBB users which is completely unacceptable.

2) SUPERPOSITION SCHEME

To address the limitation of the conventional puncturing scheme for resource scheduling of URLLC and eMBB traffic on a shared channel, a superposition technique has been realized [104]. Precisely, a new power domain NOMA method is conceptualized to superpose URLLC and eMBB traffic at the BS and perform decoding at the user end via SIC technique [105]. This method comprehensively helps in maintaining the reliability and latency ratio between broadband and delay-sensitive traffic. In comparison to the puncturing scheme, it demonstrates superior performance when the channel metrics of eMBB and URLLC users greatly differ from each other, while puncturing scheduling remains preferable when the channel gains of both services are similar.

3) ORTHOGONAL SCHEME

Two conventional reservation approaches, i.e., semi-static reservation and dynamic reservation have been conceived in which a group of frequency resources is booked in advance to URLLC transmission. The techniques show

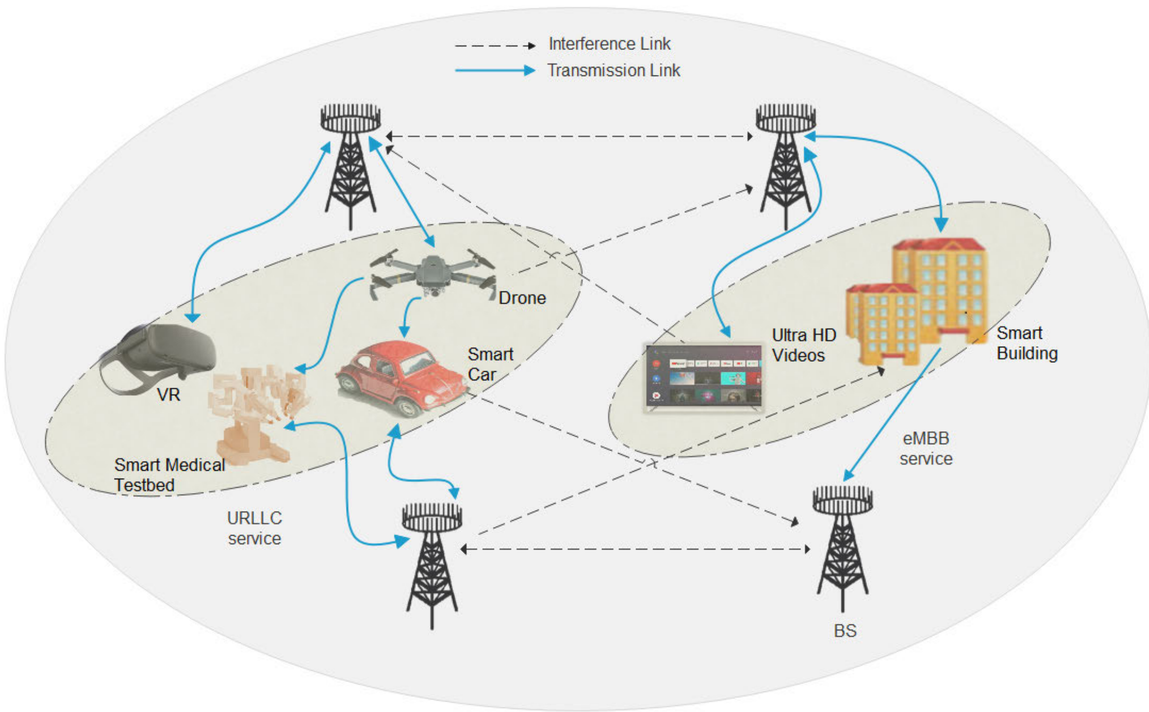

FIGURE 2. Interference scenario in co-existence of eMBB and URLLC users.

superior performance for delay-sensitive traffic but with certain shortcomings. For example, semi-static reservation intermittently sends the configuration of packet frame for instance numerology configuration, while in a dynamic reservation, the information of frame size is updated at regular intervals by utilizing the control channel sequences of a scheduled user. One disadvantage of the dynamic reservation scheme is that the reserved resources will be wasted if there is no URLLC traffic. Moreover, both schemes constitute tremendous computing time problems which are not admissible in B5G/6G activities [106].

B. ASSOCIATED CHALLENGES

Various authors devised futuristic smart techniques to handle the drawbacks of the joint transmission of eMBB and URLLC traffic. Some of the current interference issues and mitigation schemes in the co-existence of eMBB-URLLC are discussed in this section.

1) SCHEDULING AND INTERFERENCE ISSUES

The co-existence of 5G wireless specified sets, URLLC and eMBB, on the same radio spectrum introduces different scheduling and interference optimization hurdles. A null-space-based spatial preemptive scheduling for joint URLLC and eMBB traffic was proposed for ultra-dense 5G networks by researchers in [107]. It exposed the system's spatial DoF to offer interference-free subspace for URLLC traffic. The proposed scheduler provided extremely superior URLLC performance against the traditional scheduler available in the literature. Subsequently, a null-space-based preemptive scheduling scheme for joint eMBB-URLLC traffic was designed and results validated the 5G defined URLLC latency, preserved for sufficient SINR level, and improved overall SE [108], while an enhanced version of null-space preemptive scheduler has been implemented for the same joint service set traffic [109]. The outcome of the extended framework accomplished robustness in the URLLC class, maximized achievable eMBB capacity, and offered the best eMBB carrier-to-interference ratio (CIR).

2) SCHEDULING IN DENSE NETWORKS

A novel scheduling scheme that cross-optimizes the network performance on a user-centric basis has been demonstrated in [110]. The authors have designed a joint multi-user preemptive scheduling algorithm for dense 5G systems and showed that both URLLC and eMBB services received satisfactory performance under controlled inter-user interference. Besides, an in-depth system-level analysis has been steered on the usage of preemptive scheduling for latency-sensitive traffic in the availability of eMBB services in multi-cell 5G NR systems in [111]. Authors assumed minimum mean square error-interference rejection combining (MMSE-IRC) Rx at the terminal for SINR calculation at each subcarrier symbol besides 0.143 ms (2-symbol mini-slot) for low-latency communications and 1 ms for broadband (two slots of 7-symbols) assumed for TTI sizes. Performance experimental level exhibited that eMBB data rates decrease as the URLLC traffic increases because of prioritizing low-latency traffic. Thus, eMBB packets are recovered by applying enhanced hybrid automatic repeat request (HARQ) retransmission protocols and provide approximately 30% higher eMBB throughput in comparison to baseline HARQ mechanisms. Besides, two 3GPP Rel-16 proposed techniques: uplink (UL) power control and UL preemptive indication to assist dynamic URLLC and eMBB multiplexing in the UL have been discussed in [112]. Two sets of open-loop power control, one is an interference-free and the next is an interference-limited scenario, have been configured for URLLC users. The authors have broadly explained the design and performance parameters of both techniques along with the arguments. After system and link level simulation analysis, the authors illustrated that UL PI is more effective than enhanced power control in terms of URLLC capacity and efficiency of resource utilization.

3) BROADBAND NETWORK IN PROXIMITY OF SMART FACTORY

A performance evaluation study has been performed wherein the smart factory network and eMBB macro network exist in the same vicinity [102]. The authors analyzed the performance of both systems under different TDD and network load levels and via simulation results showed that high downlink (DL) interference from macro BSs towards the factory access point (AP) which resulted in an overall degradation of DL and UL URLLC traffic in synchronized and unsynchronized TDD systems, respectively. In [113], a similar study on the unsynchronized deployment of non-public URLLC factory and public eMBB macro networks under the same vicinity has been discussed. Researchers have performed simulation test by managing UL power control and confirmed that an unsynchronized setting is certainly possible with appropriate isolation between the two networks, while further stated that though a synchronized deployment can avoid cross-link interference (CLI) probabilities but still susceptible to the near-far interference. Concisely, authors suggested that smart factory locale should be deployed on a different frequency set if unsynchronized deployment is necessary. Similarly, the authors [114] have proposed the prioritization method and derived an SINR model for superior URLLC and eMBB performance. The proposed approach helped in perfect isolation for URLLC traffic even in a dynamically switching environment and confirmed that reliability may indeed be acquired by the efficient selection of NR 5G BS density and antenna elements.

Certainly, the optimum selection of BSs in an uncoordinated small cell architecture of modern wireless networks is of paramount importance. Principally, because the small cell design enables a large number of BS with the low-power transmission, the large-scale deployment of low-power BSs in the short distance along with smart devices becomes a reason for the frequent signal interruptions.

Table 4 summarizes the research work related to interference under the co-existence of URLLC/eMBB.

VI. SMALL CELLS ARCHITECTURE

The single macrocell network architecture has been evidently exposed to support massive data explosion, extreme reliability, very low-latency, a multitude of new use cases, and empowerment of advanced radio access technologies [115]. To subdue the deficiencies, a novel small cell architecture [116] was conceptualized and it certainly possesses extraordinary qualities that can enable several unprecedented real-time response applications of B5G/6G wireless networks with minimum power dissipation and pave the way for green communication [117]. The uncoordinated different sizes of low-power nodes (as shown in Table 5) can efficiently handle the diversified smart devices for three major classes, i.e., broadband, delay-sensitive, and intelligent machines activities (as shown in Fig. 3) [118], [119].

The small cell architecture allows the reuse of precious spectrum resources, yet robust resource management and allocation strategies, to furnish diverse low-to-high BW delay-sensitive applications, under the co-existence of various other wireless activities are still demandable [120]. Similarly, the deployment of varied sizes of low-power BSs, and the presence of numerous smart nodes at short distances from each other commendably introduce different interference problems [121]. Therefore, incompetent resource allocation and interference management techniques can devastatingly impair the expected network performance, user experience, and resource utilization. Taking account of URLLC cases, different types of communication options in line with the reliability, scalability, E2E latency, throughput performance, interference management, and spectrum utilization requirements have been introduced such as closed-loop communication [122], open-loop communication [123], and grant free access [124], which are discussed in the sections below.

Table 5 presents the specifications of different sizes of small cells performing various wireless access activities in an HetNet environment.

A. COMMUNICATION MODES OF URLLC

For the enablement of URLLC services, different innovative communication models have been presented to satisfy the strict latency/reliability/throughput requirements and overcome the limitations of conventional wireless communication systems. Some of the state-of-the-art communication protocols discussed in the literature are presented in this section.

1) CLOSED-LOOP COMMUNICATION

Formerly, cellular network solutions were mainly focused on the enhancement of SE and user experience for data transmission links by using several coordinated muting or power control methods while offering fewer advantages for control channel quality [125]. Alternatively, the URLLC model calls for fast-paced coordination and link-acquiring processes for enhanced performance in both data and control channels. Likewise, traditional 4G LTE and LTE-Advanced (LTE-A) were prominently manifested to achieve superior throughput performance that can accomplish highly reliable

TABLE 4. Summary of related literature of interference in co-existence of URLLC-eMBB.

Ref.	Problem/Issue	Methodology	Outcome/Advantages	Limitation/Future Work
Scheduling and Interference Issue				
[107]	Efficient scheduling problem in the simultaneous eMBB-URLLC operation	A null-space-based spatial preemptive scheduling in multi-user 5G networks	The analytical expression confirmed strict URLLC performance and greatly improved ergodic capacity	A detailed study on improving the eMBB capacity left as a future enhancement
[108]	Attempted to fulfill a contraint-coupled objective to ensure URLLC and eMBB criteria	A null-space-based preemptive scheduler framework designed	Guaranteed URLLC latency requirements and significantly improved eMBB performance	A comprehensive analysis of the proposed scheduler scheme under multi-user interference
[109]	Discussed scheduling, inter-user interference, and inter-cell interference (ICI) issue of URLLC-eMBB users on a shared spectrum	An enhanced null-space-based preemptive scheduling algorithm has been used for the co-existence of URLLC-eMBB traffic	The proposed scheduler satisfied URLLC latency and achieved an average gain of $\sim 3.2dB$ in the eMBB post-detection CIR ratio	URLLC decoding SINR level degraded by the URLLC-eMBB multi-user (MU)-MIMO transmission
Scheduling in Dense Networks				
[110]	Demonstrated fundamental trade-offs between system SE and achievable latency in joint eMBB-URLLC services	Designed a multi-user preemptive scheduler for dense 5G systems	The proposed scheduler achieved a 62% gain in average cell throughput, and superior URLLC performance by increasing the number of antennas, and reduced inter-user interference	Need a comprehensive assessment of the computational complexity and energy consumption of a system
[111]	Presented system-level performance evaluation of preemptive scheduling of low-latency traffic in the presence of eMBB users	For low-latency traffic, a bursty 50-byte stochastic mode designed along with different HARQ retransmission mechanisms proposed	Achieved 2 Mbps/cell load for low-latency transmission and enhanced HARQ techniques support 30% better eMBB throughput compared to baseline HARQ scheme	Effects of CN delays and TCP flow process was not included in extremely low-latency traffic
[112]	Explained design principles, use cases, implementation issues, and pros and cons of two 3GPP Rel-16 developed techniques	An innovative preemption and superposition scheme which allows dynamic multiplexing of the two services in an interleaved way	System-level and link-level simulation answers validated the UL PI agility over enhanced power control based on URLLC capacity and resource utilization improvement	URLLC performance achieved at the high-level processing cost of eMBB users
Broadband Network in Proximity of Smart Factory				
[102]	Interference assessment of factory ultra-reliability and low-latency (URLL) and macro eMBB network in the same vicinity	Evaluation of the performance under two scenarios: (i) synchronized TDD and (ii) unsynchronized TDD	Displayed that high DL interference from macro BSs towards the factory resulted in DL URLLC metrics reduction in TDD synchronized while UL URLLC capacity and availability reduced in unsynchronized TDD	Investigation and evaluation of interference coordination techniques both in time and frequency mode is a critical subject to explore
[113]	Understand the feasibility of public eMBB and non-public URLLC in co-location and the impact of interference	Designed a model to conduct performance assessment and evaluate network conditions	Showed the possibility of unsynchronized deployment but with proper isolation between networks and confirmed that unsynchronized deployment only possible if the factory should be is deployed on an isolated frequency	Further exploration using heavy BW UL URLLC traffic, wherein only control information is transmitted in the DL direction is required
[114]	Observed simultaneous support of URLLC and eMBB services in an industrial case	Designed an explicit prioritization technique and constructed an analytical model	Achieved perfect isolation for URLLC data traffic and defined that a maximum loss level of 10^{-6} may be attained in dense scenario via advanced antenna arrays at NR BS	In the industrial production line, only UL traffic was optimized and assumed no monitoring traffic in the DL stream

link connectivity, yet at the expense of a complex closed-loop protocol stack and high latency [126]. In closed-loop protocol, the Tx is permitted to retransmit the packets and the Rx is required to send an acknowledgment for successful reception of each packet in control channels due to wireless environmental challenges [122]. Herein, the permissibility of retransmission and acknowledgment of every received packet incur unacceptably lengthy delays and, thus, lead to an overall latency issue. For example in an LTE multi-cell closed-loop scenario, the feedback control process and backbone links inevitably result in approximately $10 - 100$ ms networking latency. Therefore, realizing a new system model that overcomes the shortcomings of closed-loop architecture has become imperative.

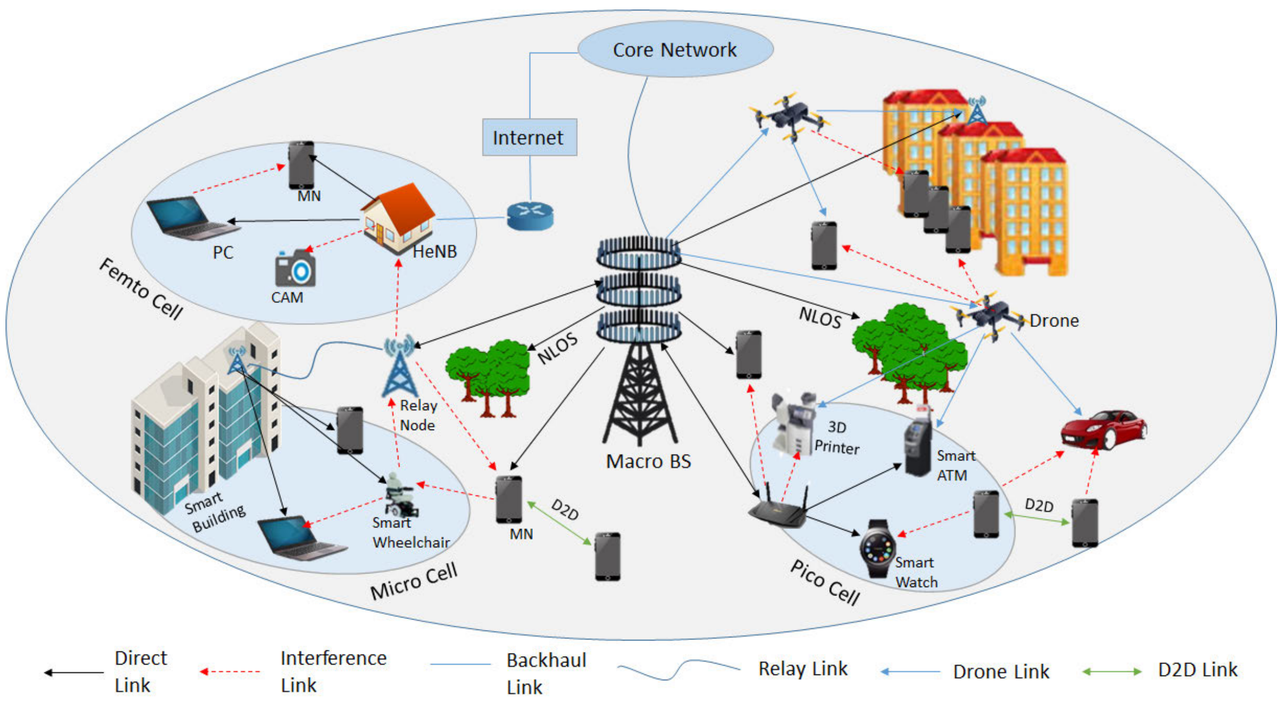

FIGURE 3. Interference limited multi-tier HetNet system comprises of URLLC, eMBB, and machine-type communication nodes.

2) OPEN-LOOP COMMUNICATION

The open-loop communication (OLC) model has gained massive attention due to its benefits over closed-loop design and its ability to cope with challenging latency constraints. Principally, in open-loop mode, the Rx does not need to provide any feedback response and the Tx does not need to schedule the retransmission of packets. Avoiding feedback and retransmission requests allows the Rx to spend more time on the computing process [127]. To be precise, OLC possesses tremendous benefits in alleviating control signal overheads and reducing high latency problems. Nonetheless, the OLC mode has shown a deficiency in maintaining reliability owing to the lack of feedback process [128].

3) GRANT FREE ACCESS

The grant-based scheduling mode is triggered by the user to demand access to the network wherein the BS responds by granting access after following a four-stage random access process. This whole procedure from initiation to scheduling takes at least 10 ms duration even before commencing the symbol transmission, which is way beyond the standards of delay-sensitive latency requirements. Since LTE uses a grant-based scheduling method wherein two-way handshaking protocols incur latency costs, thus it is really tough to accomplish the strict URLLC latency requirements. For NR 5G systems, grant free access is realized as a promising solution to overcome the grant-based mode and meet stringent URLLC requirements, especially for UL transmission. However, the grant free access mode sometimes leads to agility loss and receives access failures which are mainly observed due to two causes: i) pilot training cannot be acknowledged by the receiving BS (received SINR level is lower than the minimum threshold SINR value), and ii) collision occurs because two or more same pilots are received simultaneously at the BS (and BS could not decode any collided pilots).

TABLE 5. Specification of small cells in HetNet.

Nodes	Coverage Range	Transmit Power	Backhaul	Deployment
Femto-cell	< 50m	<23 dBm	IP	indoor
Pico-cell	< 300m	23-30 dBm	X2 interface	in/outdoor
Relay	300 m	30 dBm	wireless	in/outdoor
Micro-cell	<= 500m	<40 dBm	X2 interface	in/outdoor
RRH	few km	<=46 dBm	fiber	outdoor
Macro-cell	few km	46 dBm	S1 interface	outdoor

B. ASSOCIATED CHALLENGES

Modern communication protocols pose inherent limitations in managing interference issues which have a direct impact on the latency and reliability targets of the URLLC applications. Some of the interference issues observed in different communication models in small cell design and their minimization approaches recently presented in the literature are discussed in this section.

1) RELIABILITY ISSUE IN OLC

Deliberating the concept of virtual cells with open-loop protocol and proactive network design in vehicular networks, the authors have explained the multi-interference issues in [127]. A pseudo-ICI-Whitening method independent of ICI covariance estimation has been proposed and the BLER performance showed a practically applicable setup. Contrarily, a two-stage ICI suppression utilizing P-ICI-W and PT-ICI-W in the initial step and generalized linear minimum mean square error (GLMMSE) in the next step to further reduce the interference effects, combined with Alamouti coding to decode received signals, have been presented in [129]. The simulation test showed that the proposed method is practically suitable for OLC in DL URLLC multiple access.

A resource allocation strategy for vehicular networks under the constraint of multi-access interference has been discussed in [123]. The authors proposed virtual resource slicing and formulated the proactive allotment of resource units by using the Lyapunov optimization scheme and attained superior performance for URLLC. In [128], the authors have examined the credibility of combined OLC, multi-cell association scheme, and short blocklength regime under clustered user distribution for UL URLLC. The experimental results validated the acceptable approximation by employing the selection combining (SC) technique while the maximum ratio combining (MRC) algorithm defined stringent closed-form approximation when less than 2 BSs are associated.

2) ACCESS FAILURE IN GRANT FREE MODE

The authors in [130] derived a spatio-temporal analytical model with three different grant free HARQ mechanisms to examine the failure probability of grant free access and characterize the latency as well as the reliability performance. The experimental test confirmed that under longer latency limitations the K-repetition method achieved lower latent access failure probability while the proactive scheme achieved the same results in shorter latency constraints. Similarly, the authors in [124] have proposed two solutions: i) retransmission over a shared channel, and ii) grant free transmission with the NOMA scheme for reliability enhancement. Both proposed schemes have depicted excellent performance in achieving reliability, avoiding collisions, and enhancing resource efficiency. The combinatorial code designs (CCD) performance has been observed for UL Poisson arrival traffic for URLLC in a factory locale under the interference channel model [131]. The system-level analysis suggested that the gains achieved by using deterministic access codes based on CCDs support higher communication rates with stringent success probability. However, the high-frequency complementary metal oxide semiconductor (CMOS) on-chip antenna design and phased array technologies are future of the mobile communication, and it is prudent to evaluate the performance of high-frequency communication with modern antenna design for delay-sensitive arenas under the influence of interference and different blockage constraints.

Table 6 shows the summary of the research work of interference in small cells for URLLC in the literature discussed in this section.

VII. HIGH-FREQUENCY COMMUNICATION

MmWave spectrum is an inevitable part of the current mobile access network due to its proficiency in rich scattering environments and exclusive support of high BW applications in all indoor and outdoor mobile communication systems [132], [133]. The availability of the 30 - 300 GHz mmWave spectrum allows the realization of many delay-critical applications with extreme throughput and a 99.99% reliability [134]. However, not all of the available spectrum can be utilized for data communication purposes. For example, the 57 - 64 GHz range is susceptible to oxygen absorption, whereas 164 - 200 GHz lies in the water vapor absorption zone [135]. Also, the manufacturing cost and antenna hardware design to perfectly capture the 1 mm to 10 mm size wavelength signals at the receive antenna is a challenging task [136]. Despite this, communications over the mmWave bands can be done reliably by employing high-gain and fast-switching advanced electrical steerable antennas, while somehow it overcomes the additional free space path-loss by exploiting multipath diversity and multiple antenna streams in comparison to the sub-6 GHz frequency bands, and thus higher frequency domain is imperative for B5G workplace [137].

In the beginning, URLLC was classified for low BW applications only, with short packets that do not demand high data rates and hence, access to the mmWave frequency channel. Motivated by on-demand QoE requirements imposed by several future wireless ecosystems, industrial landscape, and immersive multimedia realities [138]; researchers from the academia and industry have agreed that URLLC systems now must be linked with higher spectrum bands that can support extremely high data rates with latency up to sub-ms.

A. FREQUENCY BANDS

1) BEYOND 60 GHz SPECTRUM

The higher frequency regime at 60 GHz (Industrial, Scientific, and Medical (ISM)) band has been nominated as a promising mmWave unlicensed spectrum to cover a wide range of applications of industry 4.0 and beyond. The Wireless Gigabit Alliance (WiGig) has included the 60 GHz band under IEEE standards of 802.11ad and 802.11ay. This 60 GHz unlicensed frequency spectrum has a great potential to unleash many time-critical high BW use cases, especially in indoor environments, due to the usage of low chip-area/cost, low power, high-amplifier gain, and very-low noise phased array antenna transceiver designs. For example, reconfigurable phased array [139], fed patch [140], differential [141], and dual-polarized dual-

TABLE 6. Summary of related literature of interference in small cells for URLLC.

Ref.	Problem/Issue	Methodology	Outcome/Advantages	Limitation/Future Work
Reliability Issue in OLC				
[127]	Examined the performance of Asynchronous URLLC DL	Proposed Pseudo-ICI-Whitening method	Increased reliability by achieving high bit error rate (BER) performance for both 2-AP and 3-AP cases, also outclassed the P-ICI-W, PT-ICI-W, and T-ICI-W schemes	A learning-based technique with multi-antenna APs for further improvement need to be investigated
[129]	Mitigation of interference and performance enhancement of autonomous vehicles	Two-stage ICI suppression and Alamouti coding proposed	Alamouti showed smaller gain but benefits of projection matrix make it suitable for OLC DL URLLC multiple access	Examined in a multi-scenario M-MIMO scheme
[123]	Resource allocation and multi-access interference problem in vehicular OLC mode	Virtual resource slicing along with proactive resource unit allotment proposed	Maximized data success probability and minimized packet collisions under the limitation of network stability	Algorithmic design and computational complexities
[128]	Analyzed the performance of OLC mode, short packet, and multi-cell association under a clustered user distribution	SC and MRC diversity schemes	Achieved high reliability for MRC while acceptable results for SC for 0.05 ms transmission interval	Apply OLC mode for clustered user distribution under more practical models
Access Failure in Grant Free Mode				
[130]	Compare GF access failure probability for randomly selected user	Spatio-temporal analytical model	Low latent access failure achieved by proactive in shorter latency and K-repetition achieved in longer latency	Proposed mathematical model can apply to other modes of grant free HARQ mechanisms
[124]	Minimizing collision avoidance and enhancing reliability	grant free random access and grant free incorporates with NOMA schemes	Proposed schemes allowed to operate in overloaded systems at symbol error rate $\sim 10^{-5}$	Further investigation for cases where outage probabilities demand as low as $\sim 10^{-9}$ percentile
[131]	Considered channel collisions in a multi-point MIMO antenna fading channels in multi-cell	Received diversity combining and CCD access patterns applied	Reduced multi-user interference and gained system throughput	Extend the case for dense deployment of APs with M-MIMO antennas

beam wafer-scale transceivers [142] are the prominent phased array antenna technologies for the enablement of the 60 GHz spectrum [143].

Moreover, the mmWave-based systems, with the BF method and phased array active antenna transceivers, provide seamless connectivity, significantly minimize HARQ retransmission and packet error rate, and overall achieve low latency performance. However, efficient resource management has become a challenging task and has paramount importance in mobile communication due to the limitations in the accessibility of the spectrum. In practice, the MIMO antenna beams reuse the radio resources and generate redundant beam patterns to overcome the problem. Even under these circumstances, the connected nodes still experience high interference, because the existence of large-scale smart devices in close range and the inherently smooth addition of pencil-like mmWave beams in the neigboring RF beams, modify the signal either in phase, amplitude, or direction, destructively. In response, the WiGig alliance follows the same interference avoidance practice for the 60 GHz frequency band as used by IEEE 802.11 WiFi standard family [144].

2) VISIBLE LIGHT COMMUNICATION

Realizing the ever-growing data demand and in search of a new spectrum, visible light communication (VLC) has gained enormous attention from all research societies [145]. It has the potential to support higher throughput, reliable transmission, data security, robustness to point-to-point communication, and minimized power consumption in a limited coverage area [146], [147]. Several studies have been conducted to explore the effectiveness of VLC in different propagation environments [148], [149]. This includes modulation techniques, color planning, soft frequency reuse, bi-directional light-emitting-diode (LED) link using the TDD method, multi-access resource allocation, hybrid radio network, smartphone light communication, etc. Recently, the prospects of VLC in indoor and short-range transmission with extremely higher throughput have been fully demonstrated in studies [150], [151]. Moving forward, focusing on a more complicated multi-point system wherein transceivers simultaneously transmit and receive data from multiple optical Tx_s and Rx_s, are readily benefitted from superior space-division multiplexing gain because the propagation range of visible light is spatially confined [152]. However, the density of APs is usually high in VLC networks, in order to ensure high coverage, rendering co-channel interference a serious issue in VLC networks [153].

B. USE-CASES

1) SMART FACTORY

The mobile communication industry is already investing heavily in designing radio systems that can operate on mmWave frequency channels. The NR 5G mmWave specifications have various features for fast access to the channel, fast processing to react instantly, and fast transmission mechanism to ensure packet drop rate of less than 10^{-5} services [154]. These functionalities can provide high data rates in B5G scenarios, e.g., factory automation [155].

For instance, many manufacturing and production processes demand stringent two-way control information exchange between sensors and actuators attached to the automated systems. These messages must be transmitted with ultra-high reliability to ensure manufacturing accuracy. In the case of consecutive packets loss, the process could be malfunctioned, resulting in a major loss of productivity. Therefore, a lot of interest has been developed in expanding mmWave bands for factory automation with appropriate transmission protocols. The ultra-wide upper spectrum of narrow beams can easily follow the directed path and avoid nearby interference. However, small-size millimeter wavelengths undergo continuous blockages due to limited diffraction achieved around the objects and high phase noise [156], [157]. Hence, factory automation and other critical time-sensitive cases demand deep analysis of mmWave and THz spectrums propagation characteristics to be effectively deployed in several RAN environments [158].

2) SMART GRID SYSTEM

The smart grid (SG) is a flexible intelligent network that performs assorted operational and energy measurement tasks to enhance the quality of distribution of electricity in power grid systems. It exclusively demands ultra-low round trip transmission delay for real-time processing and controlling of information. The SG commonly utilizes agile metering and communication architecture which rely on either radio or power line communication (PLC) approach. Following the recent advancement of 5G/B5G wireless technologies, the researchers [159] validated that the incorporation of a wireless system with SG can introduce several benefits in terms of installation, flexibility, coverage area, and cost-effectiveness. On the other hand, PLC-based schemes pose challenges in regard to transmission links, distribution lines, and frequent loss of signals [160].

Lately, after contemplating the requirements of SG and witnessing the practical benefits of mmWave technology in many wireless scenarios, the integration of mmWave frequencies in SG systems has been considered a promising paradigm. In specific, it has the potential to meet SG's strict data handling criteria such as real-time manipulation of information with ultra-low transmission latency, lower packet error rate probability, security, and cost-effectiveness. Despite its numerous advantages, radio communication may suffer in SG systems, because the high interference and reuse of spatial resources significantly increase resource scheduling issues. It is the current demand in SG networks to dispense methodical and cohesive schemes to tackle the challenges.

C. ASSOCIATED CHALLENGES

High-frequency bands frequently encounter scattering, fading, coverage limitations, attenuation, penetration, and interference issues. Some of the recently presented studies in the literature on the implementation of high-frequency bands for URLLC under interference constraints are discussed in this section.

1) HIGH-FREQUENCY LIMITATIONS IN DIFFERENT SERVICES

Under the co-existence and spectrum sharing between eMBB and URLLC service environment, a novel mmWave URLLC system has been developed. A non-orthogonal co-existence multi-connectivity scheme for eMBB and URLLC user's fairness and optimal algorithms for URLLC-eMBB design have been proposed in [161]. According to the authors, to eliminate inter-service interference between two air interfaces, the BF technique can be leveraged to attain precise directivity gain. The presented simulation tests validated the superior performance of achieving higher throughput while ensuring the latency and reliability requirements of URLLC users over the traditional co-existence scenarios. In [162], the impact of dynamic blockages, BLER, high signal-to-noise ratio (SNR) for line-of-sight (LOS), and low for non-line-of-sight (NLOS) on URLLC model roles in mmWave 5G networks was demonstrated. A joint method of neural network-based coordinated multipoint (CoMP) clustering for reliability, channel modeling to capture the spatio-temporal variations of the blockages, and enhanced control flow setup for backhaul and latency constraints have been studied. The results evidently displayed the superior performance of the implemented schemes over existing mechanisms.

Likewise, in indoor and outdoor mmWave scenarios wherein high reliability and minimized delay are of utmost importance. A resilient fronthaul link comprised of free-space-optics (FSO), and analog radio-over-fiber (A-RoF) is considered beneficial. Considering the same case, a unique coordinated mapping and combining (CMC)-based hybrid mmWave/FSO A-RoF model for ultra-reliable OFDM fiber wireless signal transport has been investigated [163]. By mitigating system impairments due to time/frequency burst interference, the authors have presented experimentally that the proposed method explicitly improved power margins and system agility.

Furthermore, a SG system has been perceived as an intelligent and swift power transmission network for delivering electrical power systems. In particular, it jointly supports electricity links and information, besides helping in maintaining the reliability of the electric transmission system. The data transportation of the communication structure of the SG may include PLC which are vulnerable to strong RF energy interference losses. In the article [164], outage probability of smart metering system (SMS) has been studied in an indoor mmWave communication scenario. The authors endeavored a 3D stochastic blockage model and conducted SINR analysis for performance measurement. The numerical results demonstrated that the reliability of the system improves in a low SINR threshold regime by simply increasing m_L (where m_L is the Nakagami-fading parameter of the NLOS of the reference Tx's channel). On the other hand, at high SINR values, the quality of the overall network deteriorates in terms of reliability, by increasing m_L.

2) HIGH-FREQUENCY SIGNAL PROPAGATION CONSTRAINTS

A new BS diversity and CoMP-style measurement have been performed in the dense urban scenario at 73 GHz spectrum, under NLOS, LOS, and interference phenomenon [165]. The authors asserted via experimental results that the probability of Rx signal attained 100% reception by simultaneous support of five BSs. Moreover, a NOMA-based SIC Rx in 60 GHz radio-over-fiber (RoF) cellular networks has been proposed in [166]. In this regard, a DSP-based SIC scheme has been implemented on the Rx side to cancel destructive interference from other users. At 4 Gbps DL data service for three users under 60 GHz band verified the enhanced reception quality and reliability of the proposed framework.

Table 7 shows the summary of the research work on the high-frequency spectrum for URLLC in the literature discussed in this section.

VIII. OPEN ISSUES AND FUTURE RESEARCH DIRECTIONS

The research classes and standardization process for upcoming 6G networks are in the infancy stage. Whilst NR 5G cellular networks still demand concrete solutions and further enhancement in various aspects of different services, especially URLLC. Hence, numerous open issues call for deep analysis and robust mechanisms for ensuring to meet the KPIs of B5G cellular networks. Some of the challenges of discussed topics sustained in current 5G systems and probable threats in upcoming 6G scenarios by reliability, availability, and latency are summarized below.

A. ENERGY AND DELAY MANAGEMENT IN SPECTRUM SHARING

Many of the 5G and next decade 6G wireless services and applications require reliable and low-latency tactile feedback and extremely higher throughput for 360° videos [18]. Meanwhile, miniaturization and compressed structural formation of electronic and sensing technologies have contracted the size of smart devices. In highly compact wireless devices, battery-life is a critical problem and a serious bottleneck for enabling high data rate URLLC. Modern AR/VR and pertinent applications require further investigation on the fundamental trade-offs among latency, throughput, seamless connectivity, and channel reliability in communications, computing systems, and user interfaces as well as haptic codecs [167], [168].

Another promising area of research is on a detailed study of URLLC delay and EE in the unlicensed spectrum, for example, the 60 GHz band. In an unlicensed spectrum, regulations need to sense the channel on a continuous basis to obtain data propagation opportunities and impose a limit on the maximum transmission time. Such limiting factors hamper both latency and EE performance and call for advanced solutions for URLLC models [58].

B. 3D BASE STATION AND LARGE BANDWIDTH ACCESS

The 6G networks are expected to support 3D deployments and activities such as 3D BSs, thus, research into data-driven modeling and assessment of the propagation environment is critical. Since 3D network planning and frequency utilization are significantly different from the conventional 2D networks, an optimization procedure is required that handles rate, reliability, consistency, latency, and SE effectively [54].

In the HetNet environment, mmWave bands are used to access large BW applications. In this regard, ultra-high reliability besides maintaining link quality is a crucial challenge, especially for vehicular users. A blockage prediction and efficient handoff to adjacent BS without any interruption has been devised with the help of ML algorithm, as a result, achieved strong reliability in mmWave links [169]. The proposed solution achieved excellent results in terms of reliability and lower latency but the technique was dependent on the single user assumption.

C. SECURITY

Future B5G and 6G URLLC wireless systems will heavily suffer from various types of attacks from nearby sources and that would result in RF channel transmission inefficiency [170]. A well-known and widely accepted cryptography algorithm is considered to work as a wall against malicious attacks in mobile networks. However, the proposed algorithm perform heavy complex algorithmic calculations

TABLE 7. Summary of related literature of high-frequency spectrum for URLLC.

Ref.	Problem/Issue	Methodology	Outcome/Advantages	Limitation/Future Work
High-Frequency Limitations in Different Services				
[161]	Evaluate the performance of URLLC in the coexistence of eMBB under mmWave services	A novel non-orthogonal coexistence method was presented to ensure fairness for users and spectrum utilization efficiency	Significantly reduced the interference effects and fully achieved the reliability and latency requirements under carrier frequency/BW of 28 GHz/2 GHz with 12 dB of shadowing effect	A more complex case, where each URLLC user can reuse the resources from multiple eMBB users and vice versa
[162]	Anticipate frequent and dynamic blockages, SNR, and BLER in mmWave 5G networks	A learning-based CoMP clustering algorithm was applied and a stochastic geometry model was used to characterize the real-world spatio-temporal blockages	The proposed techniques achieved higher throughput performance over the existing schemes	In the proposed model all BSs communicate via fiber optical link and work could be expanded for a wireless mmWave backhaul communication
[163]	Enhance mmWave signal reliability in B5G mobile fronthaul links	CMC-based hybrid mmWave/FSO A-RoF model for OFDM fiber wireless RF signal transmission	Experimental results demonstrated 9 dB received optical power gain and 5.8 dB lower EVM floor under 20 MHz LTE interference burst, and improved signaling reliability	Evaluation of power management and signaling cost is needed
[164]	Observe interference issue in the UL mmWave communication between smart meters and a gateway	Derived outage probability by employing 3D stochastic blockage model	The analysis confirmed that the probability that an SM is in LOS decreases exponentially with the link length and the count of blockages	Consider SIC for future enhancement. Also, this work can be extended for the non-convex blockage model
High-Frequency Signal Propagation Constraints				
[165]	A large-scale propagation study conducted at 73 GHz in an urban microcell open environment on New York University campus	Signal reception probabilities derived from 1 to 5 BSs that serves solo Rx location besides LOS and NLOS directional path loss models were derived, 70 and 150 half-power beamwidths (HPBW) were used at Tx and Rx respectively	Probability of signal reception at single-serving BS 55.6% observed while the maximum 100% probability achieved by Rx at five number of serving BSs	Spatial lobes, angular spread, a temporal delay, and more, from the AP diversity measurement, are left as potential work
[166]	Improvement in performance of multi-user under different channel conditions	NOMA with DSP-based SIC scheme presented in mmWave RoF system	Achieved better reception quality, 100% angle tolerance improvement, enhanced reliability without damaging data rate or altering transmission power	Consider the same process for D2D enabled FD mmWave higher spectrum with imperfect self-interference (SI) cancellation and under heavy interference event

and may not be suitable for URLLC, especially for latency-dependent IoT devices. Within this context, in a short blocklength regime over a wiretap channel, a maximal secret communication rate was derived [171] and bench test received satisfactory trade-offs among reliability, delay, and security.

D. TACTILE INTERNET

Tactile Internet (TI) is realized as a new model that will manage a plethora of new classes in real-time for B5G/6G applications. It will provide a smooth platform for humans, machines, and IoT to interact with their own environment under a limited spatial range with extreme reliability, availability, and high precision time sensitivity. Nonetheless, a highly lossy propagation environment in haptic interaction would result in erroneous sensing and frequent interruptions in online activity [172]. In the literature, many factors are highlighted that affect the reliability of TI applications such as uncontrollable interference, lack of resources, hardware malfunction, and signal strength reduction. Thus, detailed analysis and strong solutions are needed for ensuring ultra-high reliability in real-time operations [173].

Moreover, to meet the sub-ms E2E latencies in the TI paradigm, it is necessary to fathom the time-lapse budget between actuators and sensors. This would allow learning the impact of each contributing factor in the chain. Generally, E2E latency is dominated by interference issues and HARQ retransmission, backhaul links, air interface, and core latencies. To cater to the latency requirements, innovative and efficient latency minimization mechanisms are necessary.

E. DISTRIBUTED LEARNING

It is an eminent task to explore where the learning agent should be located in vehicular networks. Precisely, performing intense computation learning tasks solely on a vehicular product is not an efficient approach to knowing the computation resource constraints. Meanwhile, the high mobility of vehicles will cause really poor real-time response and can deteriorate QoE. Fortunately, with the advancement in computing abilities of smart devices, it is predicted that many smart nodes would be endowed with the capability of inferring and training the ML model in near future [174]. Therefore, a focus on the examination of distributed learning in vehicular networks to achieve intelligence on a smart product is much needed [175].

F. FEDERATED LEARNING

A substantial effort has been aimed at the usage of autonomous systems for different purposes such as smart transportation, efficient resource delivery system, and online multimedia streaming. The federated learning (FL) approaches have proved to be a resourceful tool for highly efficient performance with very minimal learning overhead. Yet, further optimization in computation learning and scheduling techniques for the cooperative ML tasks either on the smart devices or edge nodes is still needed [176]. Moreover, most of the available FL-based solutions have used labeled data sets for a variety of applications [177]. Whereas, in delay-sensitive real environment scenarios, it is tough to have high-quality labeled data set, and thus promising approaches to address such shortcomings are required [178].

IX. CONCLUSION

In the highly dynamic ultra-dense HetNet, various new technologies and robust approaches have been introduced for the performance optimization of diverse services. URLLC is one prominent and important service model of B5G/6G radio networks. However, the concurrent operation of diversified radio technologies and different service cases have manifested numerous types of interference problems. This article has broadly discussed various types of interference challenges classified according to their deployment, design, technology, usage, and propagation characteristics in URLLC. This includes inter-service interference in the co-existence of eMBB and URLLC users, ICI and multi-access interference in small cell design, and high-intensity interference in high-frequency communications. Besides, this article has indicated the future extreme throughput performance under very low-latency and up to 10^{-9} percentile success probability applications. In conclusion, this comprehensive review article has discussed state-of-the-art, open issues, and potential future research directions concerning interference management problems in broadband, flexible, scalable, and extreme URLLC classes in B5G and upcoming 6G networks.

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MARAJ UDDIN AHMED SIDDIQUI (Graduate Student Member, IEEE) received the B.S. degree in electronics engineering from the Sir Syed University of Engineering and Technology, Karachi, Pakistan, in 2010, the M.Eng.St. degree in telecommunications engineering from the University of Wollongong, Wollongong, Australia, in 2013, and the Master of Business degree in engineering management from the University of Western Sydney, Sydney, Australia, in 2015. He is currently pursuing the Ph.D. degree with the James Watt School of Engineering, University of Glasgow, Glasgow, U.K. He was a Research Associate with the National Center for Cyber Security, Computer and Information Systems Engineering Department, NED University, Karachi, in 2021. He was a Network Engineer with Orient Energy Systems Pvt. Ltd., Karachi, from 2018 to 2022. His research interests include interference management, high-frequency communication, multiple access techniques, reconfigurable intelligent surfaces, optical communication, and artificial intelligence for the optimization of future wireless networks.

HANAA ABUMARSHOUD (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees in electrical and computer engineering from Khalifa University, United Arab Emirates, in 2013 and 2017, respectively. She is currently a Lecturer (an Assistant Professor) with the James Watt School of Engineering, University of Glasgow, Glasgow, U.K. Prior to that, she was a Postdoctoral Research Associate with the LiFi Research and Development Centre, University of Strathclyde, from 2020 to 2022, and the University of Edinburgh, from 2017 to 2020. Her research interests include the application of information theory and signal processing techniques in visible light communications and LiFi systems, with a particular focus on intelligent communications, resource allocation, multi-user access, and physical layer security. She was a recipient of the IEEE TAOS Best Paper Award, in 2022. She is an Associate Editor of IEEE Communications Letters.

LINA BARIAH (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees in communications engineering from Khalifa University, Abu Dhabi, United Arab Emirates, in 2015 and 2018, respectively. She was a Visiting Researcher with the Department of Systems and Computer Engineering, Carleton University, Ottawa, ON, Canada, in 2019, and an affiliate Research Fellow with the James Watt School of Engineering, University of Glasgow, Glasgow, U.K. She is currently a Senior Researcher with the Technology Innovation Institute, a Visiting Research Scientist with Khalifa University, and an affiliate Researcher with University at Albany, Albany, NY, USA. She is also a Senior Member of the IEEE Communications Society, IEEE Vehicular Technology Society, and IEEE Women in Engineering. She was a member of the Technical Program Committee of a number of IEEE conferences, such as ICC and GLOBECOM. She is also organizing/chairing a number of workshops. She is also the session chair and an active reviewer for numerous IEEE conferences and journals. She is currently an Associate Editor of the IEEE Communication Letters and the IEEE Open Journal of the Communications Society and an Area Editor of *Physical Communication* (Elsevier). She is also a Guest Editor of *IEEE Network Magazine* and *RS Open Journal on Innovative Communication Technologies* (RS-OJICT).

SAMI MUHAIDAT (Senior Member, IEEE) received the Ph.D. degree in electrical and computer engineering from the University of Waterloo, Waterloo, ON, Canada, in 2006. From 2007 to 2008, he was a NSERC Postdoctoral Fellow with the Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada. From 2008 to 2012, he was an Assistant Professor with the School of Engineering Science, Simon Fraser University, Burnaby, BC, Canada. He is currently a Professor with Khalifa University, Abu Dhabi, United Arab Emirates, and an Adjunct Professor with Carleton University, Ottawa, ON, Canada. His research interests include advanced digital signal processing techniques for wireless communications, intelligent surfaces, MIMO, optical communications, massive multiple access techniques, backscatter communications, and machine learning for communications. He is currently an Area Editor of the IEEE Transactions on Communications, a Guest Editor of the *IEEE Network* Special Issue on ''Native Artificial Intelligence in Integrated Terrestrial and Non-Terrestrial Networks in 6G'' and a Guest Editor of the IEEE Open Journal of Vehicular Technology Special Issue on ''Recent Advances in Security and Privacy for 6G Networks.'' He was a Senior Editor and an Editor of the IEEE Communications Letters, an Editor of the IEEE Transactions on Communications, and an Associate Editor of the IEEE Transactions on Vehicular Technology.

MUHAMMAD ALI IMRAN (Fellow, IEEE) received the M.Sc. (Hons.) and Ph.D. degrees from the Imperial College London, London, U.K., in 2002 and 2007, respectively. He is currently the Dean of the University of Glasgow, U.K., UESTC, the Head of the Autonomous Systems and Connectivity Division, and a Professor in communication systems with the James Watt School of Engineering, University of Glasgow, Glasgow. He is an affiliate Professor with The University of Oklahoma, Norman, OK, USA, and the 5G Innovation Centre, University of Surrey, Guildford, U.K. He is leading research with the Scotland 5G Centre, University of Glasgow. He has published more than 20 years of combined academic and industry experience with several leading roles in multi-million pounds funded projects, working primarily in the research areas of cellular communication systems. He has authored or coauthored more than 500 journals and conference publications and has supervised more than 50 successful Ph.D. graduates. He was a recipient of an Award of Excellence in recognition of his academic achievements, conferred by the President of Pakistan. He was also a recipient of the IEEE Comsoc's Fred Ellersick Award, in 2014, FEPS Learning and Teaching Award, in 2014, Sentinel of Science Award, in 2016, and ten patents. He is a fellow of the Royal Society of Edinburgh, a fellow of the Institution of Engineering and Technology, a fellow of the Royal Society of Arts, and a Senior Fellow of the Higher Education Academy. He is the speciality Chief Editor of the IoT Section of *Frontiers in Communications and Networks* and an Associate Editor of IEEE Transactions on Communications. Previously, he served in editorial roles for the IEEE Communications Letters, IEEE Access, and *IET Communications*.

LINA MOHJAZI (Senior Member, IEEE) received the B.Sc. (Hons.) degree in electrical and electronic engineering from United Arab Emirates (UAE) University, Al Ain, United Arab Emirates, in 2008, the M.Sc. degree (Hons.) in electrical and electronic engineering from Khalifa University, Abu Dhabi, United Arab Emirates, in 2012, and the Ph.D. degree in electrical and electronic engineering from the Institute for Communication Systems, University of Surrey, Guildford, U.K., in 2018. She is currently an Assistant Professor (a Lecturer) with the James Watt School of Engineering, University of Glasgow, Glasgow, U.K. Her research interests include beyond 5G wireless technologies, physical-layer optimization and performance analysis, wireless power transfer, machine learning for future wireless systems, and reconfigurable intelligent surfaces. She is also an Associate Editor of the IEEE Communications Letters and IEEE Open Journal of the Communications Society. She is an affiliate member of the Mohammed bin Rashid Academy of Scientists, United Arab Emirates, and a fellow of the Women's Engineering Society.

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