Unlocking Unlicensed Band Potential to Enable URLLC in Cloud Robotics for Ubiquitous IoT

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ABSTRACT

Cloud robotics (CR) support extremely high reliability and low-latency communications in ubiquitous Internet of Things applications. However, many of those applications currently rely on wired connection, limiting their use within the confines of Ethernet/optical links. Some wireless solutions such as Wi-Fi have been considered, but failed to meet the stringent criteria for latency and outage. On the other hand, cellular technology possesses expensive licensing. Thus, the Third Generation Partnership Project (3GPP) is actively working on New Radio in the unlicensed band for incorporating ultra-reliable low-latency communications (URLLC) into fifth generation and beyond communication networks. In this article, we aim to study the feasibility of URLLC in an unlicensed band specifically for CR applications. We open up various use cases and opportunities offered by the unlicensed band in achieving latency and reliability constraints for robotics applications. We then review the regulatory requirements of unlicensed band operation imposed by 3GPP and explore its medium access challenges for CR due to the shared use of unstable wireless channels. Finally, we discuss the potential technology enablers to achieve URLLC using the unlicensed band for the ubiquitous CR applications.

INTRODUCTION

Fifth generation and beyond (5GB) wireless communication promises to transform the potential of cellular technology rather than merely increase the data rates and enlarge the coverage as preceding generations have done. The Third Generation Partnership Project (3GPP) will achieve this by entirely transforming the way cellular networks are constructed, the nodes they can link to, their operating frequencies, and the role they represent. Robotics and automation technologies will be its significant beneficiaries in ubiquitous Internet of Things (IoT) applications. As 5GB enables wireless control of highly sophisticated mobile machines, the possibility for robots to take advantage of the enormous computing power and storage available in the cloud without physical wires becomes feasible. Equipped with these functionalities, robots can be accurately controlled dynamically in near real time. This is also termed as cloud robotics (CR). Furthermore, CR provides access to open source, massive databases and applications, mutual learning resources through information sharing, and crowdsourcing human intelligence. The recent progress in CR has led to ubiquitous robotics applications in different mission-critical domains such as industry, medical, and transportation [1], which are highlighted below.

Industrial robotics: The 5GB-enabled robots will find a place on the manufacturing floor to boost industrial automation [2]. Smarter robots can execute a significant number of tasks in the manufacturing process, which could be remotely controlled and monitored in the cloud. Industrial robots are already commonplace, but the advent of 5GB will enable the creation of an "intelligent factory," where the manufacturing platform is run by a fully automated system based on information and communication technology. Moreover, artificial-intelligence-operated robots using a varying network slice can navigate the intelligent factory without rails/tracks. Cloud computing can be used to offload the resource-consuming robotic movement tasks, while others, especially complicated tasks, can be operated safely alongside human intervention.

Medical robotics: One of the most critical applications for 5GB in robotics is healthcare. The robots will not only perform general tasks like transferring medical objects from one position to another based on 5GB and cloud computing, but 5GB-based robots can also perform tele-surgery and tele-operation [3]. Telepresence surgery is not entirely new; however, 5GB will enable it to actually happen in real time and with higher accuracy. Specialists from more than one location could undertake surgery on a patient at a distant location. This technology could save lives, especially in emergency situations, where time is precious and transportation is impossible.

Vehicular robotics: Fully intelligent and autonomous vehicles (IAVs) will soon hit the road; they will act as robots, because they can perform instructions from a wide range of sensors to make critical decisions. Unmanned aerial vehicles (UAVs), and other terrestrial vehicles also fit into this category [1]. In vehicular technology, the cloud can facilitate IAV with desirable information, including traffic events, road conditions, weather, directions, GPS, speeds, and so on. Moreover, one can build a network of IAVs using vehicular clouds to perform different computing tasks to achieve distinct utility functions such as real-time information, which cannot be performed locally. An IAV that is connected to the cloud through

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Use cases	Industrial robotics/ automation	Healthcare	Vehicular robotics/ autonomous car/ITS
Latency (ms)	0.25 ~ 10/50 ~ 100	30	1/5/10 ~ 100
Reliability (%)	99.9999999/99.99	99.999	99/99.999/99.999
Data size (bytes)	10 ~ 300/40 ~ 100	28 ~ 1400	144/1600/50 ~ 200
Communication range (m)	50 ~ 100/100 ~ 500	300 ~ 500	400/300/30 ~ 1000

TABLE 1. CR use cases and key performance index [3, 4].

5GB can use machine learning techniques to perform tasks without being explicitly programmed beforehand.

CR technology not only requires a massive amount of information to be uploaded and downloaded from the cloud, but the system is also susceptible to lost data packets. For the realization of CR, 5GB has been working on extremely low-latency, highly reliable communication technology named ultra-reliable low-latency communication (URLLC) technology. URLLC is machine-type communication that involves a massive number of connected things with strict constraints on reliability and latency set to 99.999 percent and 1 ms, respectively. There are various aspects of delay. The user plane latency is the time for effectively transmitting an application layer packet or message from the service data unit entrance point to the equivalent exit point at the radio protocol layer. End-to-end (E2E) includes contributions to the user plane delay, application computation time, and network transport latency. Similarly, reliability is evaluated based on the packet error rate (PER) of the incoming signal. The PER is the ratio of the total number of packets with errors or lost at the receiving side to the total number of transmitted packets (i.e., lower PER means higher reliability). Based on the above definitions, the key performance index of URLLC defined by 5GB is shown in Table 1.

There has been a lot of research on URLLC [4–6]. In the 3GPP standards Releases 14 and 15, specifications have been proposed to support URLLC in the licensed spectrum. Release 16 has studied URLLC for the unlicensed spectrum. We present a brief review of the techniques and specifications for URLLC. The most common approaches for minimizing delay are:

- Grant-free (GF) transmission by eliminating unnecessary scheduling request (SR) and resource grant time
- Reducing turnaround time between downlink (DL) and uplink (UL) by allowing turnaround within a frame
- Reducing latency in hybrid automatic repeat request (HARQ) process through joint HARQ acknowledgment (ACK) for several DL transmissions and HARQ-ACK feedback in the same time slot
- Decreasing transmission time interval (TTI) through larger subcarrier spaces
- Reducing the overall processing time through less number of orthogonal frequency-division multiplexing symbols in TTI and parallel computation

Similarly, the approaches to achieve high-reliability are:

- Data/frame replication, redundancy through multiple radios or channels
- Multiple-input multiple-output and beamforming for spatial diversity
- Spreading and coding to increase robustness against interference and noise

Supports for higher bands, side-links, edge computing, and so on are currently being defined for New Radio-Unlicensed (NR-U) in Release 17.

Nearly all the literature on URLLC guidelines presumes the use of licensed spectrum. The unique problems and challenges with unlicensed spectrum are barely touched. Achieving URLLC appears to be more challenging in unlicensed spectrum, as reliability and latency are tightly interconnected (i.e., retransmissions can realize reliability, but retransmission increases the latency extensively). Table 2 gives a brief review of the URLLC research work in unlicensed band. All of these studies share common information. The channel access processes are expected to induce increased delays, because data transmission is often postponed due to high interference. Therefore, promoting strict latency-reliability criteria for standalone unlicensed spectrum remains an issue that requires more research and developmental investigation. The main contributions of the article are as follows:

- We study the feasibility of unlicensed band for URLLC communication in various CR applications such as industrial, medical, and vehicular robotics.
- We open up diverse opportunities provided by unlicensed band along with challenges for CR applications.
- We explore unlicensed band medium access protocol challenges imposed by 3GPP regulatory requirements and possible extension for CR applications.
- As a case study, through simulation, we show that the latency on unlicensed channel access procedure (i.e., CAT4 LBT) is highly unsuitable for CR as it has a high probability of missing URLLC deadlines.
- We discuss the potential technology enablers to achieve URLLC in CR.

Unlicensed Band Opportunities to Achieve URLLC for CR

The dawn of CR has shifted robotic systems from research lab to becoming a low-cost, time- and energy-saving element of automotive, healthcare, and other industries by placing intelligence in the cloud and simplified robotics on the ground. Communication technology is a key enabler in connecting the cloud-based system to the robots and controllers. For modern robotics applications, the ability to design wireless networks to meet performance (i.e., latency and reliability) and security requirements of critical applications is fundamental to the new wave of cyber-physical systems.

Role of the unlicensed band in increasing reliability: The unlicensed spectrum has mostly been regarded as a valuable asset to raise cellular operators' capacity and coverage. However, it can also be considered as an alternative and diverse source to improve reliability in CR communication for accurate operations of robots. As data communication, reliability, and availability can be improved by redundancy, various paths can be formed in an unlicensed band by diversity

Paper	Contributions	Technology	Frequency	Application	Coexistence	Medium access	Transmission
[7]	Multi-channel strategies	Load based LBT	5GHz	Augmented reality/IAV	Yes	GF/SR	DL/UL
[6]	Latency in LBT is analyzed	Multefire/LBT CAT4	2.4/5GHz	Industrial Smart-grids IAV	Yes	GF	DL
[8]	Delay from CCA, LBT HARQ retrasnmission	Multefire CAT4&2	5GHz (indoor)	Industrial	No	GF	DL
[9]	Latency due to CAT2 LBT failure prior HARQ; compared GF and SR transmission	Multefire (CAT4,2&1)	5GHz	Industrial	No	GF/SR	DL/UL
[10]	Use of license spectrum for delayed packet	Multefire CAT3	5GHz (indoor)	Industrial	No	GF	UL
[5]	Compares GF and SR	Multefire CAT3	5GHz (indoor)	Industrial	Yes	GF/SR	UL
[2]	Use of both unlicensed and license bands	N/A	N/A (indoor)	Factory	Yes	N/A	DL/UL

TABLE 2. Summary of the URLLC model in unlicensed band.

of space, frequency, or time. Any combination of the paths can be used for data redundancy to improve data availability and resilience. Hence, combining multiple paths can provide better protection against loss or erroneous data from fading and interference, which are critical problems of CR in the mobile environment. Reference [10] discussed time-domain redundancy of data for increasing reliability, whereas in [6, 7], frequency domain redundancy was considered.

The unlicensed frequency band enables private wireless technology to be deployed with reduced cost as well as efficient deployments in comparison to the licensed spectrum. The ability to operate a private network in the newly available broadband unlicensed spectrum (3.5/5/6/60 GHz) under cellular technology offers necessary network isolation, data protection, and device/user authentication, resulting in more reliable and secure means of communication for mission-critical CR applications. In addition, connectivity between access points (APs) is always coordinated in the cellular system via a core network nearby or in cloud, ensuring a seamless connection as a robot/vehicle/system transfers from one AP to another. Thus, mobile CR with mission-critical applications that necessitate continuous, reliable connections, such as safety communications and alert systems, will be supported with extremely trustworthy links.

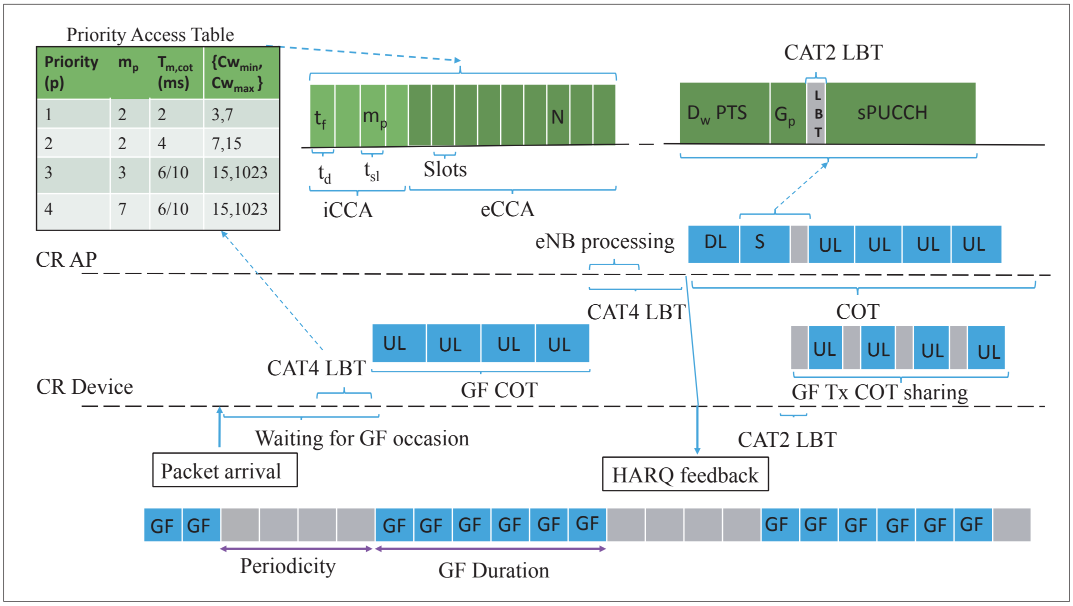
Role of unlicensed band in reducing latency: The unlicensed spectrum can reduce latency by permitting packets to be sent on less congested channels of the unlicensed band. There is abundant free spectrum, and the new spectrum is in the process of being free under unlicensed bands (600 MHz only in 5 GHz), which can be further subdivided into multiple channels of the same or different bandwidths. Thus, robots/APs can use one channel or multiple channels simultaneously for transmission. The authors of [7] introduce the *period without access*, where almost continuous transmission using multiple sub-channels of the unlicensed band has been achieved for URLLC communication. Similarly, Long Term Evolution (LTE) and wireless local area network aggregation [11] technology can also be considered for the fastest cloud-to-robot DL transmission.

The introduction of IoT devices for automation purposes in robotics applications has increased the number of sensors per square meter, making a high-capacity network almost mandatory. For instance, device-to-device (D2D) communications enables direct connections instead of connecting via the AP. D2D communication in the overlay process is possible in the unlicensed spectrum where D2D services are committed to the AP schedules if arranged and accomplished within the channel occupancy time (COT) of the AP. This type of scheduling would reduce the latency to almost half by decreasing the number of hops from two to one, thereby facilitating URLLC in a highly dense environment.

CR Operation on the Unlicensed Band

The use of an unlicensed spectrum for CR communication will follow Multefire protocol, whose specifications are now being considered as NR-U [12]. The standalone operation of CR systems in the unlicensed band dramatically adds to the deployment flexibility, providing a single global framework, where services are not only possible in the existing 5 GHz (5150–5925 MHz) spectrum, but also in the new 3.5/5/6/60 GHz spectrum when they become available. The 6 GHz band is considered as the new spectrum with the highest potential as it offers hundreds of megahertz usable channels. For example, 5925–7125 MHz in the United States and the lower portion of the 6 GHz band (5925–6425 MHz) in Europe are being discussed for unlicensed operation within different regulatory standards.

As the unlicensed band is free and shared by various CR and non-CR wireless standards, different stringent regulatory requirements are imposed on CR transmission depending on the regions and specific sub-bands to circumvent interference and to guarantee fair use of resources. These requirements include limitations of CR systems on radio channels, channel selection, transmit power, and channel access regulations. Under channel access regulations, each CR system must evaluate the accessibility of channels before any transmission, known as clear channel assessment (CCA). The CCA uses the listen before talk (LBT) procedure. According to 3GPP specifications [12], a CR system intending



Priority Access Table

Priority (p)	m_p	$T_{m,cot}$ (ms)	$\{Cw_{min}, Cw_{max}\}$
1	2	2	3,7
2	2	4	7,15
3	3	6/10	15,1023
4	7	6/10	15,1023

FIGURE 1. GF LBT channel access procedure for CR devices.

to send data should first sense the channel to be idle during a defer duration t_d. The defer duration contains a fixed quota of time, t_f, with a length of 16 µs, closely followed by m_p CCA slots t_{sl} with each duration of 9 µs. The CCA slot is believed to be idle by the CR system if the energy detected is lower than a certain threshold for at least 4 µs. This is also called initial CCA (iCCA). The iCCA process is followed by extended CCA (eCCA). Throughout eCCA, the channel is observed by CR systems for *N* consecutive CCA slots known as the contention window (CW), where *N* is a random variable uniformly distributed between zero and the maximum value of the CW size.

The CR station lowers the value of the CCA counter as CCA senses an idle channel, and if it is identified as busy, the CCA counter is frozen and enters in a deferral mode also known as backoff mode. The CR system resumes the CCA counter only after the channel is sensed idle for a deferred duration. LBT is deemed successful when the CCA counter is zero. After a successful LBT, the CR system can transmit and occupy the channel for a duration equivalent to the maximum COT (MCOT). This procedure is generally referred to as category (CAT) 4 LBT. The CW differs based on the number of successful and unsuccessful number of transmissions in the channel, which are measured based on HARQ feedback transmission. Eighty percent negative HARQ transmission is considered unsuccessful. The channel access priority class classifies the different values of CW sizes, MCOT durations, and m_p as per the access group of CR traffic, as shown in Fig. 1. The transition subframe (S) between DL/UL is called a partial ending subframe (D_w*PTS*), a guard period (G_p), and a shortened UL subframe (sPUCCH).

There are also other forms of LBT (i.e., CAT1, CAT2, and CAT3 LBT). In CAT1, the replying CR system has no restriction in accessing the channel if the difference between the end of transmission of starting the CR system and the start of transmission by replying to the CR system is smaller than 16 µs. On the other hand, CAT2, mostly used for UL transmission in shared MCOT, inserts a fixed sensing duration of 25 µs. The 25 µs interval splits into a 16 µs interval containing CCA slots and 7 µs of idle slots, with extra CCA slots. CAT3 is similar to CAT4, except that CAT3 uses a fixed size CW. Figure 1 shows the channel access procedure in unlicensed band for CR systems.

For the analysis of latency associated with the channel access procedure, we perform a simulation on a CR device based on CAT4 LBT. Figure 2 shows the simulation result of complementary cumulative distribution function (CCDF) of the delay spent on performing CAT4 LBT by a CR device. The channel access priority class three with very high, high, medium, low, and very low load conditions is assumed. The term *load* refers to the probability of sensing an idle channel in the simulation. From the graph, we can see that for high load situations, the CR device will spend more time performing LBT. Moreover, the graph is less steep as we go from low to high load situations; this is because of the increase in backoff mode and the probability of choosing a higher CW value. Similarly, we also study the overall E2E delay of the DL CR packet correctly received for various values of retransmission for the medium load condition. Figure 3 shows that due to high dependency on LBT and HARQ delays, the CR packets have a higher probability of missing the URLLC deadline as the packet needs more retransmissions.

Challenges in the Unlicensed Band for CR

Recently, spectrum is becoming extremely rare. Any CR devices using unlicensed spectrum are obliged to comply with strict regulatory requirements. Thus, the shared use of unpredictable channels is limiting its application in operation-intensive robotics environments. We highlight some important challenges here.

Challenge Due to Shared Use

The well-known 2.4 GHz and 5 GHz unlicensed bands are shared by various wireless standards such as LTE, Wi-Fi, Bluetooth, Zigbee, and the future 5GB NR-U using LBT. In the CR environment, the LBT mechanism allows only one CR/

non-CR system of any wireless standard (who won the contention scheme) to access the channel. Thus, other competing systems have to defer their transmission until the ongoing CR/non-CR system has finished communication. If one of the CR devices in the robotic application tends to have critical information to send, it is delayed. The delay time relies on how fast the ongoing CR/non-CR system (of same/different standard) finishes its transmissions. Moreover, inside the same network standard, there might be additional devices/ robots/APs contending for the channel simultaneously. Therefore, it is not confirmed that critical messages of CR systems will obtain access to the channel even after the deferral time on the ongoing communication. Hence, for shared spectrum access in the unlicensed bands, there is no definite accessibility of the channel. Moreover, the transmission might be affected by other CR/ non-CR users' signals even after the rescheduling period. Hence, the transmission delay and reliability do not occur at expected times in a shared band as it is difficult to control or foresee traffic of other CR/non-CR devices and standards.

Challenge of LBT Parameters

Compared to the CR licensed scheduling-based solution, the strict requirement of LBT on an unlicensed channel access procedure for CR causes higher delays and uncertainty. This is because the data transmission is frequently deferred due to high measured interference from competing CR/ non-CR devices. As discussed earlier, LBT constitutes a CCA procedure, which is further divided into iCCA and eCCA procedures. The mean time used in performing CAT4 LBT by CR is the sum of the average time spent for detecting each of the *N* CCA slots as idle and the number of CCA slots that are detected throughout the iCCA slot along with a fixed portion of the defer time (i.e., 16 μs). As we know, the value CCA slots, as well as *N*, vary with the priority traffic. Hence, for the same priority traffic of CR systems, CCA time solely depends on the number of CR/non-CR devices contending for the medium. In the highest load situation, the value of *N* increases as the probability of choosing a higher value for $CW_{\max}$ increases. Moreover, every time the channel is detected as busy, the CR device goes into backoff mode where it has to wait for an extra time interval of at least 43 μs. It does this before it starts reducing the CCA counter, making LBT highly time-consuming and unfavorable for URLLC CR communication.

Challenge of HARQ Feedback

HARQ is designed to manage potential failures and to increase the reliability in the decoding process. In HARQ, the CR transmitter is configured to automatically trigger retransmission of the CR packet if negative acknowledgments (NACKs) are received or timeout occurs. Adaptive asynchronous HARQ has been considered in which retransmission can occur at arbitrary time instants (i.e., upon LBT success). Unlike Wi-Fi, LBT in CR application does not include the request-/clear-to-send (RTS/CTS) mechanism to reduce collisions caused by hidden node problems. Thus, for robots/APs operating in unlicensed band, their communication might be affected by signals from other CR/non-CR devices at any time, increasing the NACK rate. Moreover, failure to transmit NACK/ACK (CAT2 LBT) from the CR receiver can cause additional challenges. It triggers unnecessary retransmissions for already decoded CR packets, which impact following transmissions of neighboring CR/non-CR devices by unnecessary channel access. The CR system itself is also affected by raising its queuing delay as the portion of the existing resources are not utilized efficiently for retransmissions.

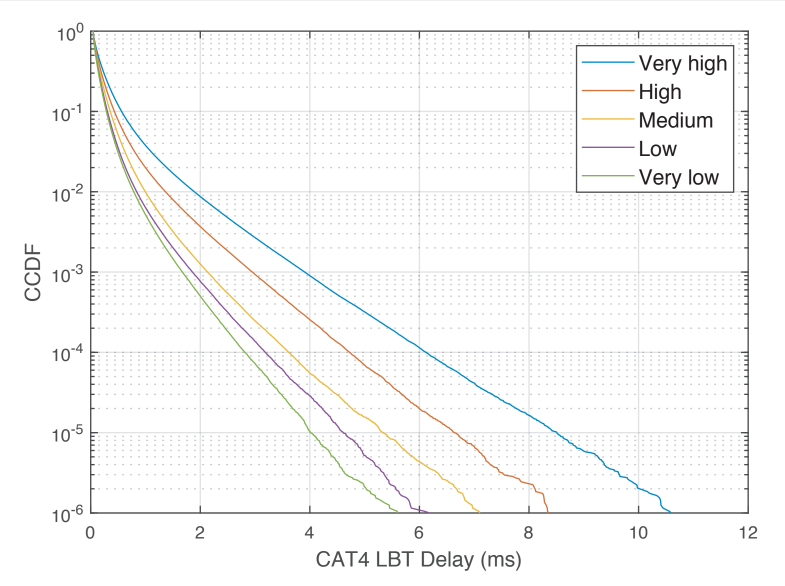


FIGURE 2. Latency of CR device performing CAT4 LBT for various load conditions.

Challenge of GF Transmission

Multefire [13] has proposed a GF UL approach in version 1.1, aiming to minimize the delay for the UL transmission by avoiding the extensive scheduling request (SR) procedure implemented in standalone unlicensed band operation. This is because avoiding the transmission of the SR information from the transmitter and the corresponding grant by the receivers decreases the number of required CCAs that each CR device must execute before any communication in the unlicensed band. With GF, the CR systems are required to transmit at particular time instances using periodic preconfigured resources, called GF resources, without sending SR and receiving any particular grant. The CR system needs to execute either CAT2 or CAT4 LBT before transmitting on GF resources, which depends on whether or not the interaction is within MCOT already attained by the serving AP. The GF resources are allocated among GF CR devices, ensuring that many CR systems will concurrently transfer their resources in the same time-frequency. For high traffic load, the probability of transmission in the same resource increases, resulting in collisions and retransmission among the CR systems. Thus, the latency associated with the binding CAT4 LBT can increase in accordance with the load, leading to worse performance than SR-based transmission for CR communications.

Enabling technologies for CR

Shared multicarrier connectivity: 2.4 GHz and 5 GHz are the most popular bands for operation in the unlicensed band. However, multiple other

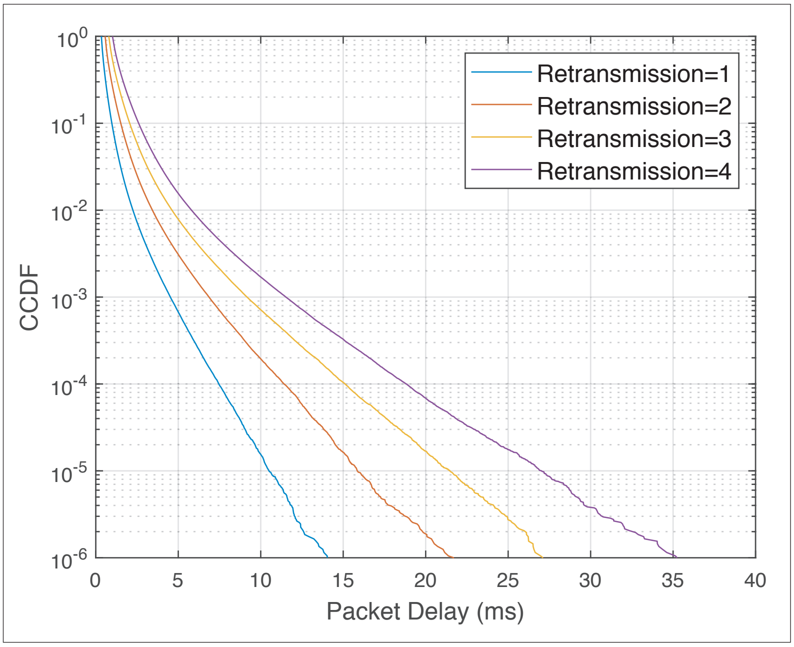


FIGURE 3. E2E packet latency of a CR device for medium load condition.

bands have recently been opened for unlicensed shared operations. They include: 3.5 GHz band (shared in the United States), 6 GHz band (unlicensed in the United States and Europe), 37 GHz band (shared in the United States), and 60 GHz band (unlicensed worldwide) [14]. Furthermore, terahertz (THz) level band is also under investigation for operation. Thus, CR communication can expand the deployment scenarios by considering more than two bands for carrier aggregation and dual connectivity. Therefore, the aggregation/connectivity with multiple shared unlicensed bands (sub-6 GHz, mmWave, and THz) can facilitate the CR system to enable a new multi-band standalone deployment scenario exclusively unlicensed to improve reliability, availability, and resilience.

Network slicing: Wireless CR communication will constitute various systems operating commonly in the unlicensed band including sensors, actuators, edge controllers, head-mounted displays, handheld terminals, cameras, and so on. These multiple CR systems have their own communication requirements. For example, a CR system might need ultra-reliable services (sensors/cameras), while others may require extremely low latency (actuators/UAVs). Thus, the unlicensed band network needs to be planned to offer a diverse mixture of capabilities to meet all these various requirements of CR systems at the same time. Intuitively, the best rational method is to make a set of specific networks, individually modified to assist one type of CR system. These dedicated networks would let the application of custom-built functions and network operation dedicated to the desire of each CR system. A more competent approach is to run numerous committed networks on a shared platform; this is effectively what "network slicing" means [4]. Thus, CR radio access network (RAN) slicing is the embodiment of the idea of operating several logical networks as virtually non-dependent activities on a common physical infrastructure efficiently and cost-effectively. Through network slicing, CR systems would be able to meet the requirements of latency-critical, availability-critical, and reliability-critical devices at the same time with high flexibility, security, and isolation.

Hybrid access: It has been proved that unlicensed spectrum can address URLLC traffic efficiently in low traffic situations. However, for a substantial CR traffic condition, it can lead to extreme delays because of collisions, even without exterior interference. Thus, opportunistic use of the licensed spectrum can be apprehended for those CR URLLC packets that cannot be assisted within a specific latency budget [2, 10]. Because a GF CR system is permissible by the existing 5 GB technology, emergency CR URLLC traffic does not have to wait for scheduling grants in the licensed band. Thus, a group of 5GB resources can be held back for URLLC, and the CR packets can be transmitted by choosing a resource randomly. The collisions might be possible between the CR systems, and appropriate magnitude of resources is required for confirming the reliability restriction. Hence, the minimum amount of additional license resources should be calculated in advance to meet the performance requirements of CR applications.

Mobile edge computing (MEC): MEC is a promising approach for timely delivery of computation-intensive tasks offloaded from mobile robotics, hence decreasing the end-to-end delay. Edge computing devices can be set up at CR access controller points that are nearer to industrial robots than data servers/clouds [1]. MEC near data sources can incorporate different CR device interfaces and behave as a raw data filter. The edge computing system has the benefit of being able to offload certain computationally intensive jobs to the edge node instead of the distant cloud. Thus, edge computing can overcome the limitations of CR. The protocol stack is a key future research direction for seamlessly integrating edge computing into the new paradigm of cellular technology in the unlicensed band for CR applications.

Machine learning (ML): The shared multi-carrier connectivity, network slicing, edge computing, and hybrid access increases the efficiency of CR operation in the unlicensed band. Moreover, the integration of all these technologies can be exploited to get synergistic performance gain [15]. This is a prerequisite for the collaborative and more autonomous strategies between these entities. Thus, ML-assisted CR network control that manages the complexity of the CR network autonomously is required to increase the quality, accuracy, and precision of CR communication [14]. Figure 4 details an ML-assisted integrated technologies network. However, there are further challenges to address. For example:

- The automatic selection of the most suitable carrier and/or spectrum to meet the wide variety of CR application requirements
- The amount of license resources to borrow for CR application without interfering CR or non-CR license users
- Stability of several edge learning CR controllers making decisions that can interfere with each other
- The timeliness of the automated decisions and learning processes of CR systems, in a situation where latency is a stringent requirement

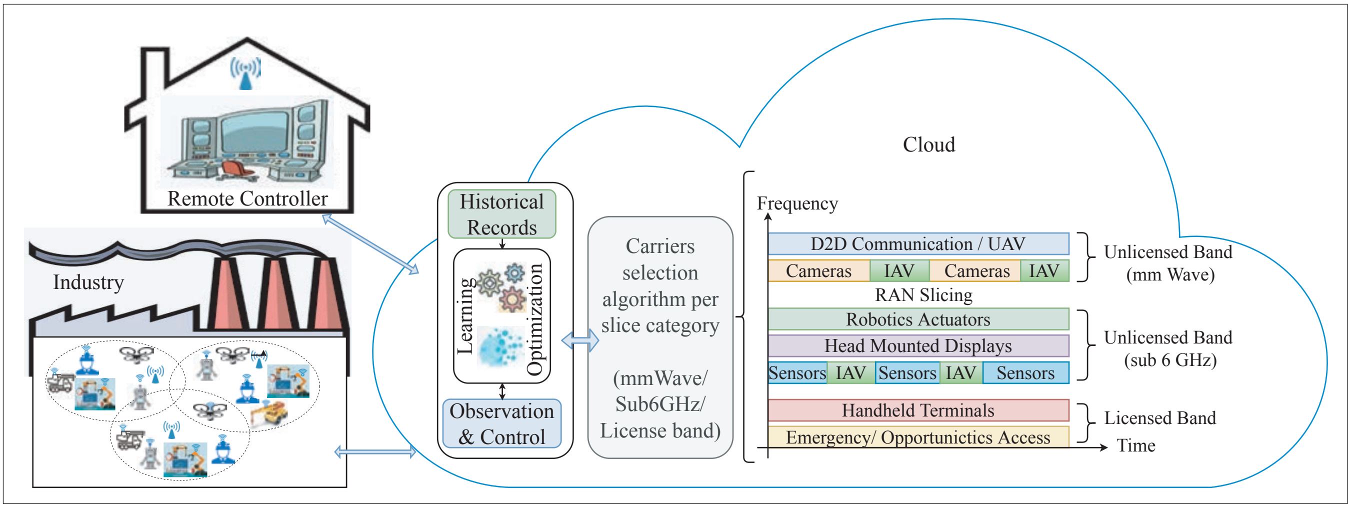


FIGURE 4. ML-assisted integrated CR enabling technologies.

CONCLUSION

This article has investigated the unlicensed band opportunities for CR that presently has no wireless solutions to meet URLLC constraints. Considering the flexibility of the wireless medium, we have shown various future use cases of CR in mission-critical applications such as industrial, automotive, and healthcare. The unlicensed band, apart from being a capacity booster, has a significant role in achieving URLLC for ubiquitous CR applications. However, due to regulatory requirements and shared use, the unlicensed band possesses a higher risk of latency and outage for CR devices. Thus, we have identified and discussed challenges for CR operating in the unlicensed band. Lastly, enabling technologies to facilitate URLLC in the unlicensed band for CR application have been discussed.

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