5G-U: Conceptualizing Integrated Utilization of Licensed and Unlicensed Spectrum for Future IoT

Xi Lu, Vitaly Petrov, Dmitri Moltchanov, Sergey Andreev, Toktam Mahmoodi, Mischa Dohler

***Abstract*—Intelligent Internet of Things (IoT) applications constitute one of the fastest developing areas in today's technology and at the same time pose the most demanding challenges for the respective radio access network design. While the initial studies in IoT were focused primarily on scaling the existing radio solutions for higher numbers of small-data and low-cost sensors, the current developments aim at supporting wearable augmented/virtual reality platforms, moving industrial robots, driving (semi-)autonomous vehicles, and flying drones, which produce large amounts of data. To satisfy these rapidly growing performance demands, the 5G-grade IoT is envisioned to increasingly employ millimeter-wave (mmWave) spectrum, where wider bandwidths promise to enable higher data rates and low-latency communication. While the mainstream trend in mmWave-based IoT is to rely on licensed bands around 28 GHz or leverage unlicensed bands at 60 GHz, we in this work introduce a conceptual vision for the integrated use of these frequencies within a single radio access system named 5G over unlicensed spectrum or 5G-U. We study the performance of 5G-U in supporting stringent IoT use cases, discuss and compare the alternative strategies for spectrum management in 5G-U, and demonstrate that a harmonized utilization of licensed and unlicensed bands provides notable performance improvements in both device- and network-centric metrics. We finally offer useful guidelines for future implementation of 5G-U and detail its potential applications in the area of advanced IoT services.**

I. Introduction

In December 2017, the first description of non-standalone 5G New Radio (NR) technology has been released by 3GPP, which included dual-connectivity operation between the existing 4G as well as the emerging 5G NR solutions. It became a part of Release 15 as a key milestone on the way to a full-fledged 5G cellular [1]. The standard description specifies a wide range of NR frequencies, from traditional 600 and 700 MHz bands to higher millimeter-wave (mmWave) spectrum. Essentially, NR features two frequency ranges: one in sub-6 GHz band, including low-bands (below 1 GHz) for indoor use and mid-bands (1 to 6 GHz) for outdoor use; and another range generally in the spectrum above 6 GHz, namely, high-bands (above 24 GHz) for outdoor use. Presently, 5G mmWave cellular bands are primarily centered on two regions, 24 to 28 GHz and 37 to 40 GHz.

Prior to these latest NR developments by 3GPP, the 60 GHz band was made available worldwide for unlicensed operation to extend the capabilities of Wi-Fi systems into mmWave frequencies. Similar to Wi-Fi, the key design goals behind this technology were the simplicity of operation by dynamically sharing the spectrum among multiple contending stations. The corresponding specification was issued by Wireless Gigabit Alliance (WiGig) in 2009 and then standardized under the IEEE 802.11 umbrella in 2012 to deliver the data rates of up to 7 Gbit/s. Even though some research efforts are underway to explore the use of advanced antenna design to improve the beamforming gains, the communication range of WiGig is still limited to 10-30 meters. Therefore, the scenarios envisioned for unlicensed-band mmWave applications are mostly related to indoor "last-meter" wireless access [2].

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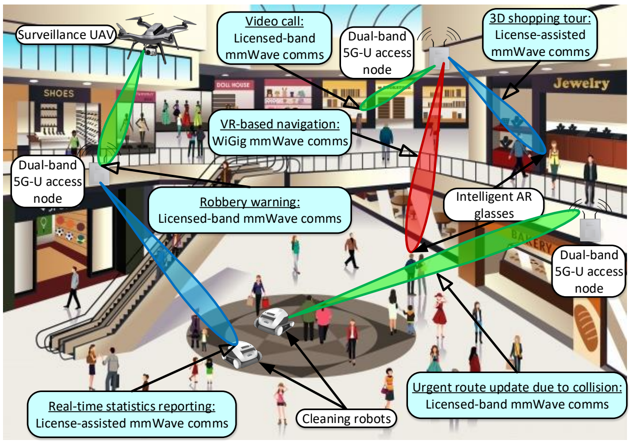

Fig. 1. Emerging IoT services in 5G and beyond.

For future 5G and beyond services, three major categories of use cases have been confirmed by the International Telecommunications Union (ITU): firstly, enhanced mobile broadband (eMBB); secondly, massive machine-type communications (mMTC); and, finally, ultra-reliable and low latency communications (URLLC). However, with increasingly dense deployments and more stringent performance requirements of emerging IoT applications [3], even the recent licensed-band NR technology and unlicensed-band WiGig systems alone may have difficulty in supporting bandwidth-hungry urban scenarios. The associated challenging use cases span a wide variety of augmented/virtual reality (AR/VR) services, live-stream multi-view 4K video, and exchange of large arrays of time-critical sensing information, among many others. While these intelligent IoT applications are still in the early stages of their market penetration, they are expected to soon generate prohibitive data loads [4].

The capacity boost promised by commercial 5G systems due to abundance of the mmWave spectrum is significant and should suffice for most contemporary user needs. However, the nature of future IoT applications forces us to continue augmenting the radio access capabilities over the years to come. The anticipated intelligent IoT applications are bandwidth-hungry and quality-of-service (QoS)-sensitive [5], while they may easily consume all of the available 5G bandwidth as we discuss below. There are multiple classes of services where the use of additional bandwidth – especially in dense urban environments – may bring significant benefits for the network operators [6].

We in this work conceptualize the integrated utilization of licensed and unlicensed mmWave spectrum to support the emerging IoT applications in urban deployments exemplified in Fig. 1. We discuss the concept of 5G Unlicensed (5G-U), where 3GPP NR employs more reliable licensed spectrum for control signaling, paging, authentication, and mobility management, while data transmissions leverage the aggregated radio resources across both licensed and unlicensed frequencies. We introduce and compare possible strategies for radio resource sharing among different categories of IoT devices, thus illustrating the benefits of 5G-U in certain advanced IoT use cases. We finally outline further steps on the way to the implementation of 5G-U and detail some prospective applications.

The rest of this article has the following structure. Section II introduces the conceptual vision of 5G operation in unlicensed spectrum, formalizes its requirements, and discusses the guiding implementation principles. Further, Section III investigates the performance potential of this proposal by concentrating on a typical urban IoT use case. Section IV then outlines the prominent emerging applications along the lines of intelligent IoT for the respective technology development, while the last section draws the main conclusions.

II. 5G in Unlicensed Bands

The increased reliance on unlicensed spectrum is becoming indispensable for the network operators in response to the escalation of mobile data demands. 3GPP and Wi-Fi Alliance, along with the device manufacturers and other involved parties, have invested much effort into exploring novel coexistence techniques for spectrum sharing starting from Release 12. Equipment developers and standardization organizations foresee the value of aggregating unlicensed spectrum within a multi-radio access network (multi-RAN), thereby providing better user experience and maintaining lower infrastructure costs.

Stemming from the premise of Carrier Aggregation (CA) and LTE-U/LAA technology, the concept of 5G operation in unlicensed bands (5G-U) advocated in this work is a natural extension of LTE-U/LAA techniques from ultra/super high frequency (UHF/SHF) bands to extremely high frequency (EHF) bands, also known as mmWave spectrum. Accordingly, 5G-U aggregates e.g., 28 GHz licensed band operation with 60 GHz unlicensed band operation [9], which was conventionally meant for IEEE 802.11ad (WiGig) systems. This pioneering approach is in-line with the recent 3GPP standardization activities on the NR Unlicensed (NR-U) technology, which commenced earlier this year [7], [8] with the goal of serving crowded areas, such as football stadiums and concert venues. In these demanding setups, reliance on 5G-U should allow for meeting the stringent data rate requirements of emerging services.

The envisaged utilization of unlicensed bands requires another degree of flexibility in the radio access technology. In 4G systems, only two types of diversity can be exploited, namely, frequency and time. In contrast, 5G-U systems can additionally employ narrower beams in conjunction with time and frequency diversity, thus additionally contributing space diversity (see Fig. 2). Similar to single-band radios, further enhancements, such as code diversity or full duplex radio capabilities, may also be considered to improve the network performance.

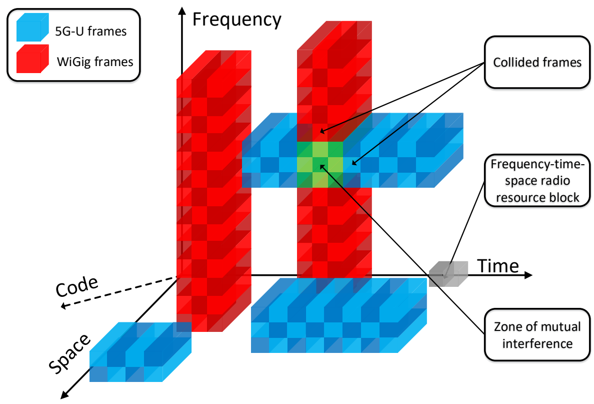

Fig. 2. Space, time, frequency, and code diversity in 5G-U.

The aggressive utilization of spatial dimension with 5G-U may dramatically improve the performance of future radio systems as compared to e.g., LTE-U/LAA. Particularly, whenever two users are well separated in space within the coverage range of a 5G-U base station, simultaneous transmissions on the same frequency are feasible under certain conditions. Furthermore, the coverage area of WiGig access points (APs) is practically limited to 10–30 m, which corresponds primarily to indoor operation. This opens the door to employing 5G-U technology in outdoor settings on the same frequencies.

With the main carrier centered at the 28 GHz frequency, theoretically, approximately 2 GHz of bandwidth is available. However, this includes data payload as well as the necessary signaling and control information, such as access overheads, authentication, mobility management, paging, registration, etc. Further accounting for the contemporary frequency regulations, a single operator is not expected to have access to more than 1 GHz of bandwidth in the licensed bands. While the frequencies between 28 GHz and 57 GHz are currently subject to heated regulatory debates, the spectrum range of 57-70 GHz is generally considered to be license-exempt. The latter offers resources for deploying not only the existing WiGig technology (6 WiGig channels, 2.16 GHz each) but also hosting hybrid solutions, such as the proposed 5G-U.

An important constraint in LTE/Wi-Fi coexistence is that the interference generated by an LTE/Wi-Fi AP on unlicensed channels remains lower than that from the incumbent Wi-Fi AP performing on the same channel. To satisfy this restriction, a number of methods have been applied, including listen-before-talk (LBT) mechanisms and schedule-based LTE operation [10]. Both of these approaches exploit time diversity to avoid direct interference between the coexisting systems. Despite massive throughput gains reported in case studies, the fulfillment of QoS – one of the most essential capabilities of LTE systems – can be assured by adopting an LBT-based mechanism.

Hence, for the prospective 5G-U systems, we envision

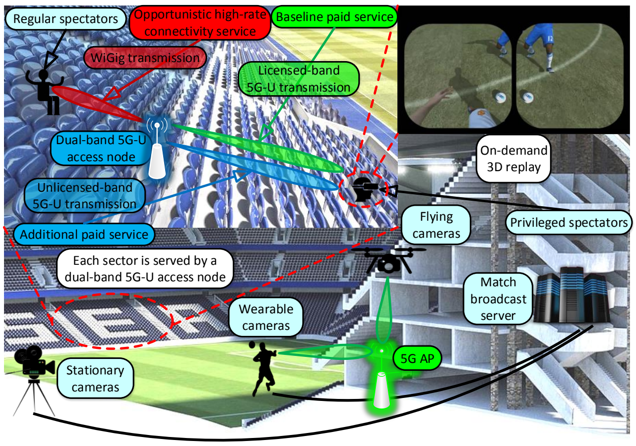

Fig. 3. Modeled 5G-U communications scenario in new Stamford Bridge.

two key requirements where a 5G-U base station should (i) not interfere more than another WiGig AP operating on the same frequencies would and (ii) provide the level of QoS comparable with the mmWave systems operating in licensed bands. Currently, two implementation regimes related to the envisioned 5G-U functionality are beginning to propagate through the latest 3GPP discussions [11]:

1) *License-assisted access*. The main thinking behind this regime is to carry most of the sensitive signaling between the network nodes over the more reliable licensed spectrum, while the delivery of data payload burdens both licensed and unlicensed bands as well as depends on the current system loading.
2) *Standalone mmWave operation.* This regime aims to develop a cellular technology operating solely in the mmWave spectrum. Accordingly, the solution must be made capable of operating over unreliable channels, which calls for more robust signaling constructions.

While the development of 5G-U technology may become a long-term endeavor for the research community, the understanding of its potential performance gains in certain scenarios should facilitate these initial efforts. Therefore, the following section delivers a case study of 5G-U operation, which aims at providing first-order performance insights as well as highlighting the implications of key system design choices. We particularly focus on the license-assisted 5G-U regime in our subsequent evaluations.

III. Assessment of a 5G-U Use Case

With the goal to understand the prospective performance gains of utilizing 5G-U, we here concentrate on a representative urban setup that may correspond to a number of practical IoT applications (see Fig. 3). In this section, we summarize our scenario of interest, its key deployment parameters, the details of our conducted evaluation, and an interpretation of the obtained numerical results.

A. Considered Scenario

In this work, we address a near-future football match, where a certain proportion of spectators utilize Extreme VR (X-VR) glasses e.g., borrowed at the stadium. This comprehensive eye-wear provides additional information on top of what the spectators can observe from their seats, such as current speed of the player driving the ball, distance to the gate, hit strength, etc. A person with X-VR glasses may also watch 3D replays of selected events (goal, fall, penalty, etc.) by exploiting the emerging virtual reality technology. We specifically focus on the latter IoT feature, since this functionality is more challenging to support from the communications perspective. In addition, the described service represents non-critical traffic that can be offloaded onto less reliable unlicensed bands in certain conditions.

All of the background data (e.g., player speed) typically has moderate volume and can thus be transferred to the X-VR devices via licensed-band radio technology with the use of contemporary multicast techniques. At the same time, 3D replays are requested by the spectators on demand and may demonstrate the scene from different viewing angles; hence, they have to rely on unicast transmissions. As we illustrate numerically later, reliable delivery of high-quality 3D replays to a substantial number of consumers cannot be performed exclusively over the licensed frequencies, and therefore X-VR glasses need to exploit 5G-U whenever appropriate. The data from WiGig-capable personal devices of people in the stadium (smartphones, cameras, etc.) is considered here as the background traffic, such that the unlicensed band is dynamically shared between the two types of transmitted information.

We concentrate on the peak demand situation that emerges when a goal is scored. Our evaluation varies the fraction of spectators wearing the X-VR glasses, named *privileged users*, from 0 to 1. Once the goal is scored, we assume that 80% of privileged users begin to watch a replay within the next 10 s. The duration of this replay is modeled as a random variable with the mean of 15 s. The considered sessions require the rate of 38.5 Mbit/s [9]. In addition, we capture regular background traffic from the WiGig-capable user equipment (UE), which has the data rate of 10 Mbit/s and transfers sessions with the mean length of 10 s. Other important numerical parameters related to our study are summarized in Table I.

In what follows, we compare three state-of-the-art strategies for spectrum management that can be followed to dynamically share the radio resources between X-VR glasses and WiGig devices:

1) *Uncoordinated.* This is a baseline strategy, where no coordination between the WiGig and 5G-U schedulers is assumed. Accordingly, the WiGig and 5G-U resource allocation is conducted independently, which may result in uncoordinated interference and subsequent drops of active sessions.
2) *WiGig priority.* This strategy assumes coordination between the WiGig and 5G-U schedulers, such that radio resource allocation for the two groups of UEs is performed jointly. Here, the priority is given to the WiGig sessions, which are being scheduled first, while the remaining available resources are granted to the 5G-U transmissions. This option highlights the performance gains made available with 5G-U when it operates in the “best effort” mode.
3) *5G-U priority.* This strategy operates similar to the previous case, but here the priority is given to the 5G-U

TABLE I
DEPLOYMENT AND TECHNOLOGY PARAMETERS IN OUR ASSESSMENT

Parameter	Value
Deployment	
Stadium sector size	300 seats
Height of dual-band access node	5 m
Height of X-VR glasses	1.25 m
Height of WiGig UE	1.1 m
Fraction of users wearing X-VR glasses	[0..1]
Traffic	
Data rate of X-VR replay sessions	38.5 Mbit/s
Data rate of WiGig sessions	10 Mbit/s
Mean duration of X-VR replay session	15 s
Mean duration of WiGig session	10 s
Fraction of X-VR glasses showing current replay	80%
Technology	
Dual-band node transmit power	23 dBm
Target SNR for non-outage conditions	3 dB
User device antenna gain	5 dB
Dual-band node antenna gain	10 dB
Licensed carrier frequency	28 GHz
Licensed channel bandwidth	1 GHz
Unlicensed carrier frequency	60 GHz
Unlicensed channel bandwidth	6 WiGig channels
WiGig channel bandwidth	2.16 GHz

data transmissions, whereas the WiGig data utilizes the remaining radio resources. Hence, the motivation is to study the full performance benefits for the X-VR users when the WiGig transmissions do not have priority.

While even more intelligent resource allocation strategies can be implemented, which account for the radio propagation conditions and the data transmission properties, this set of options is sufficiently representative to illustrate the core trade-offs in the system design within our first-order assessment.

B. Evaluation Methodology

This performance evaluation has been produced by our in-house system-level simulator (SLS) that combines all of the essential components examined in this study.

1) Software details: The core functionality of the tool is implemented in Python with the heavy use of the SciPy library for mathematical operations. The Matlab-style plots are produced directly from the Python code by utilizing the Matplotlib library. The software runs with a step-size of 0.01 s. The 5G-U- and WiGig-specific physical layers are designed according to 3GPP [7] and IEEE guidelines [12] individually, which includes 3GPP's clustered multi-path channel model for mmWave bands. Our SLS takes into account the properties of the modulation and coding schemes to be employed in 3GPP NR and IEEE technologies [13]. This instrument is a further development of the SLS tool heavily utilized in our previous work on mmWave communications [14], [15].

2) Simulation process: Whenever a new session arrives, it appears in the queue of data "waiting for transmission". The software module modeling the AP behavior allocates the frequency–space–time radio resources (see Fig. 2) for every arrived session according to the currently preferred resource allocation strategy, as specified in subsection III-A. Two or more frames are considered to experience a collision if they overlap in frequency, space, or time. This contention may result in either a successful transmission of the entire block

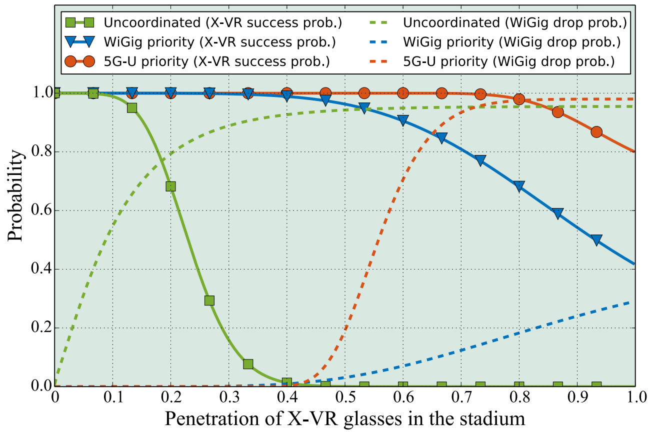

Fig. 4. Effects of X-VR gear penetration in the stadium.

of data or a failure due to a lack of resources and inadequate propagation conditions. Partially corrupted transmissions are considered unsuccessful.

3) Modeling considerations: Certain additional features were adopted to implement the radio technologies of interest. First, as we model an enclosed area (e.g., the stadium use case), no interference from the outside devices is considered. Then, as the devices are assumed to remain static for the entire duration of a simulation run, the mobility support in our SLS was disregarded to speed-up the modeling. In addition, perfect beam alignment between the nodes was assumed. The tool runs sequential dynamic simulations of the scenario in question, each producing a set of intermediate data with respect to the target metrics. Finally, all of the possessed data are averaged over 5,000 replications to achieve better accuracy.

C. Results and Implications

First, Fig. 4 demonstrates the success probability for the X-VR sessions (dotted line) and the drop probability for the WiGig sessions (dashed line) – both referred to as "probability" along the vertical axis – as functions of the penetration fraction of X-VR glasses in the stadium for the three resource sharing strategies introduced in subsection III-A. The uncoordinated scheduling of 5G-U and WiGig transmissions results in multiple collisions and hence demonstrates the worst result for both 5G-U- and WiGig-centric metrics of interest. Moreover, in our setup (see Table I), the relatively low-rate and shorter WiGig sessions are "dominated" by longer and more bandwidth-hungry 5G-U transmissions. The latter makes the drop probability for WiGig reach 90%–95% when the penetration of X-VR eye-wear is around 50%.

We continue with Fig. 5, which presents the maximum number of supported X-VR sessions per sector as a function of the number of WiGig channels that 5G-U can occupy. Since the spectators are expected to demand higher reliability for the services provided over X-VR glasses, we define the highest number of sessions as the maximum count of simultaneous X-VR streams per sector, which yields the session success rate of not lower than 99%. Studying Fig. 5, one can learn that the 5G-U priority strategy results in better numbers of supported sessions, thus ultimately reaching 231 sessions when all 6 WiGig channels are in use. The figures for the 5G-U

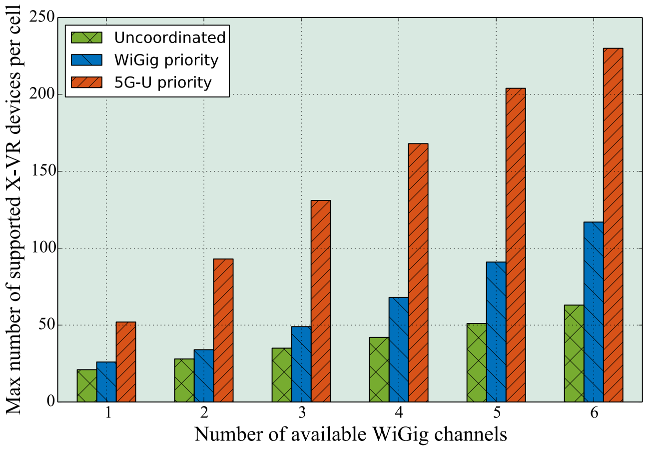

Fig. 5. Effects of the number of occupied WiGig channels.

priority strategy are almost twice as high as those obtained with the WiGig priority scheme, whereas the performance of the uncoordinated alternative is the worst and barely reaches 50 sessions for 6 available WiGig channels.

In summary, our study reveals a considerable advantage of utilizing the proposed 5G-U concept in the representative IoT/wearable scenario. It also delivers novel performance insights for two different spectrum sharing strategies, so that the operators can make informed decisions when designing their radio access networks. This includes a trade-off between the X-VR session continuity and the WiGig quality of service.

IV. Prominent 5G-U Applications

The relatively slow market acceptance of LTE-U/LAA technologies has been primarily due to a lack of compelling use cases that drive the interest of network operators. To better understand the potential of the proposed 5G-U concept, we review the types of emerging applications that may benefit the most from the 5G-U functionality. The latter becomes appealing for "value-added" services, where the basic quality level is provided in licensed spectrum while extensions are delivered over unlicensed bands.

A. *Industrial Internet*

As research on the applications of Industrial Internet is becoming more mature, it is widely acknowledged that 5G technology is playing a key role in Industry 4.0. While a major trend in consumer Internet development over the past years has been along the lines of improving the performance of reliable but still opportunistic content dissemination, future Industrial Internet deployments prepare to expedite a rapid transformation into ultra-reliable skill-set delivery networks.

Here, 5G-U solutions become most useful, since the traffic demands of e.g., industrial robots can be well separated into a relatively low-rate control/safety plane and a relatively high-rate but not as safety-critical data transmission plane. While the former clearly calls for ultra-reliable and low-latency connectivity over cellular mmWave bands, the latter can employ both licensed and (much broader) unlicensed spectrum. As an example, all of the service signaling that pertains to robotic operations (move, lift, turn, etc.) as well as the latency-critical messaging (e.g., malfunction or goods drop) can be carried out via licensed mmWave spectrum, while rich additional data from the robots (such as visual and haptic channels) may be provisioned over wider unlicensed mmWave bands.

B. *Airborne Communications*

Unmanned Aerial Vehicles (UAVs) also known as drones have recently been receiving increased research attention. The primary data produced by most of the existing drones is a high-quality video capture with built-in or carried-on cameras. While reliable video streaming from several UAVs may be supported by contemporary microwave solutions, massive video transfer from tens to hundreds of UAVs per square kilometer will become challenging even for 5G mmWave cellular systems. Therefore, 5G-U is considered attractive to effectively decouple the data transmissions from multiple flying drones in both consumer and industrial applications.

5G-U might also assist in constructing surveillance systems or emergency mission-critical services over drones. Another potential advantage of 5G-U is in the use of directional mmWave antennas that allow flying robots to avoid interference with terrestrial networks. The operators may deploy dual-band 5G-U access nodes, such that the licensed spectrum is primarily intended for the ground users (humans, connected vehicles, etc.), whereas the unlicensed bands are employed for opportunistic data transfers by flying devices. This way, the deployment costs can be notably decreased as there is no need to install and maintain dedicated network equipment for airborne applications.

C. *Extreme Augmented and Virtual Reality*

Potential usage of 5G-U for emerging AR and VR systems is in fact much broader than the stadium use case discussed in Section III. Generally, any live service in sports venues and surrounding areas that involves massive data exchange between a high number of uncoordinated IoT devices (such as AR/VR gear) becomes a use case for 5G-U. Following the "valued-added" considerations, the system can differentiate between the data streams from AR/VR glasses vs. those from conventional user devices, and accommodate them based on the effective service subscription policies.

Additionally, 5G-U can assist in real-time VR broadcasting to smart terminals, support immersive gaming, aid in online VR shopping, etc. In all of these scenarios, the crucial signaling and reliable communications are to be handled via the QoS-friendly mmWave solutions in the licensed bands, whereas the background textures and other delay-tolerant data transfers can occur over the opportunistic mmWave channels in the unlicensed spectrum.

D. *Urban V2X Communications*

Another application area of 5G-U in intelligent IoT is V2X services in urban deployments, including massive vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), and vehicle-to-infrastructure (V2I) content exchange. The V2X connectivity is considered to be a key application in the 5G systems, thereby enabling data offloading from infrastructure, increased awareness with capable vehicular sensors, along with reliable safety messaging. The next-generation vehicles have been implementing the support for emergency message transfer over microwave technologies. As a result, the aggregate traffic from radars, light detection and ranging devices (LIDARs), and visual cameras mounted on high-end cars can reach 1 TB of data per hour of driving [4].

The conventional radio technologies, such as dedicated short-range communication (DSRC), 4G-based cellular solutions, and even the upcoming 5G NR systems that operate on licensed mmWave bands, may not be sufficient to maintain the multi-Gbit/s data rates demanded by the prospective interaction of connected cars. The lack of V2X systems operating in unlicensed mmWave spectrum offers an excellent motivation for the use of 5G-U solutions to leverage all of the available bandwidth for communicating massive sensing information across autonomous vehicles. In this setting, the critical data that ensures functionality of the basic services (e.g., road/driving safety) is to be provided over the licensed spectrum, while the extra data may travel over the unlicensed mmWave bands.

V. Conclusions

The unprecedented advancements in artificial intelligence and robotics technology drastically increase the intensity as well as the depth of machine-type interactions across the IoT landscape. With the anticipated massive deployments of wearable AR and VR platforms, connected vehicles, mobile industrial robots, and flying drones, even the abundant radio resources available in licensed mmWave spectrum around 28 GHz may soon become insufficient. At the same time, the stringent QoS requirements of intelligent IoT prevent from exploiting radio technologies that operate solely in unlicensed – and hence less reliable – mmWave frequencies at 60 GHz. An integration of licensed and unlicensed band operation within a one-stop radio access solution, named here 5G Unlicensed or 5G-U may therefore offer the much needed performance benefits due to more efficient utilization of radio resources across both bands.

Our conducted analysis of attractive IoT scenarios confirms that the concept of 5G-U promises to support the order-of-magnitude higher densities of communicating IoT devices, thus essentially unlocking significant cost savings for system/service operators in terms of both the capital investments to deploy their network infrastructure and the operational expenditures to maintain it. While tighter coupling of licensed and unlicensed mmWave spectrum imposes further research and development challenges, the enormous potential of the envisioned 5G-U solution makes it a promising technology candidate for a plethora of important use cases within the field of intelligent IoT applications.

Meanwhile, 5G-U raises several important research and engineering questions, which include but are not limited to performance evaluation of 5G-U in other use cases (e.g., connected vehicles or UAVs), development of efficient interference-aware resource allocation mechanisms, design of flexible software-driven radio terminals capable of integrating multiple mmWave bands, and construction of softwarized network architectures to effectively steer heterogeneous data streams over a complex network topology with alternative multi-stream paths. This conceptual development additionally arises a number of standardization and legal concerns to maintain the security and reliability of data transmissions over inherently unreliable unlicensed bands. These example research questions become the novel directions to continue work on tailoring the 5G-U to accommodate advanced IoT services.

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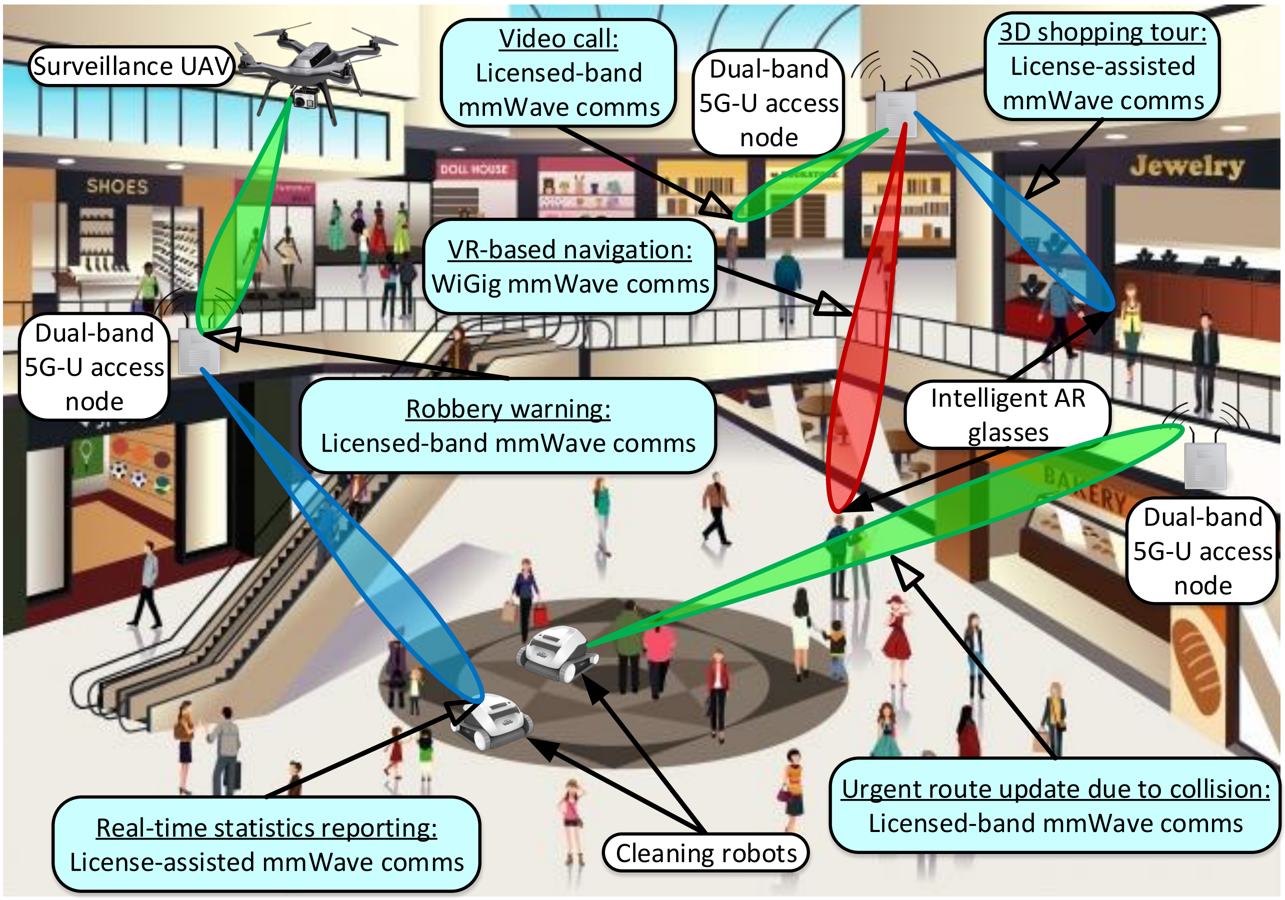

Fig. 1. Emerging IoT services in 5G and beyond.

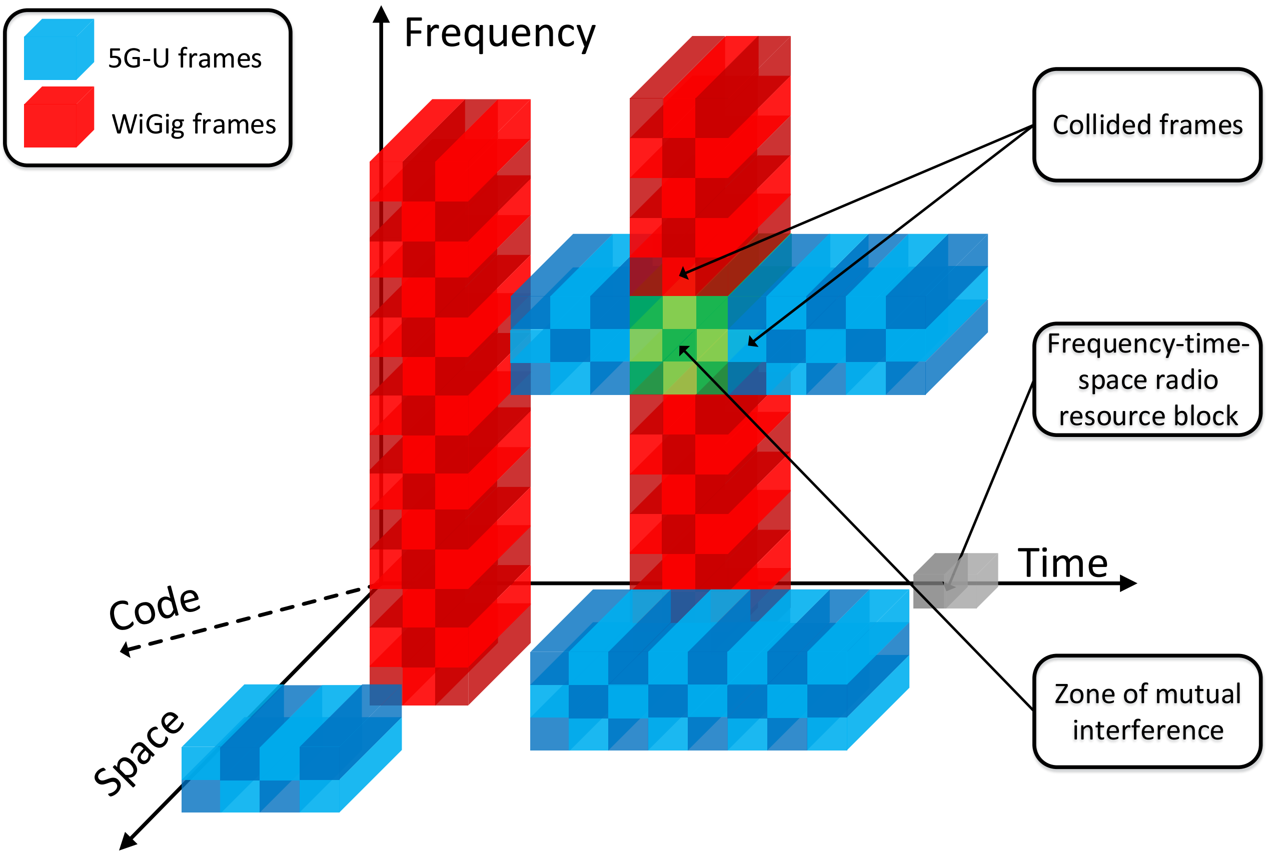

Fig. 2. Space, time, frequency, and code diversity in 5G-U.

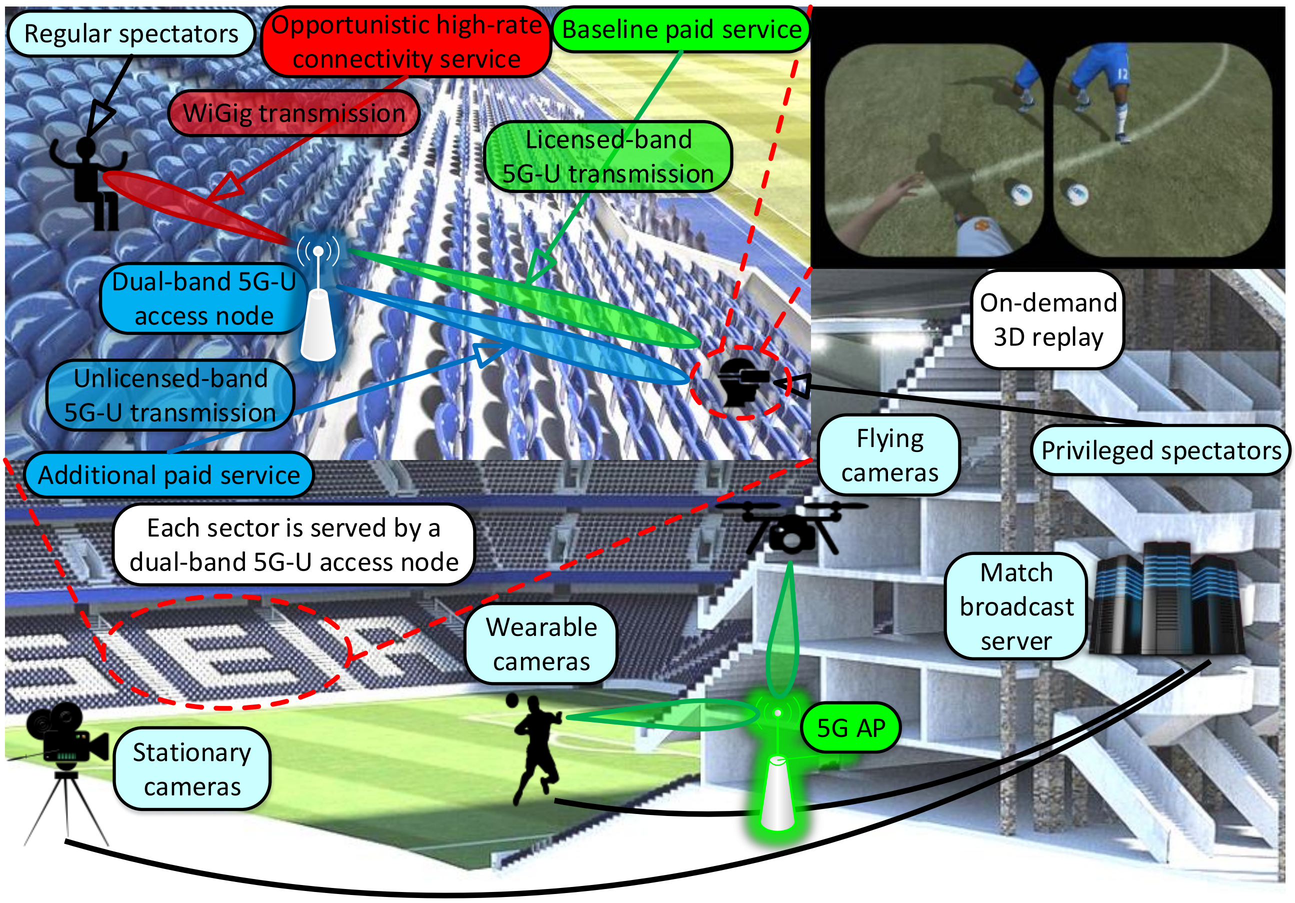

Fig. 3. Modeled 5G-U communications scenario in new Stamford Bridge.

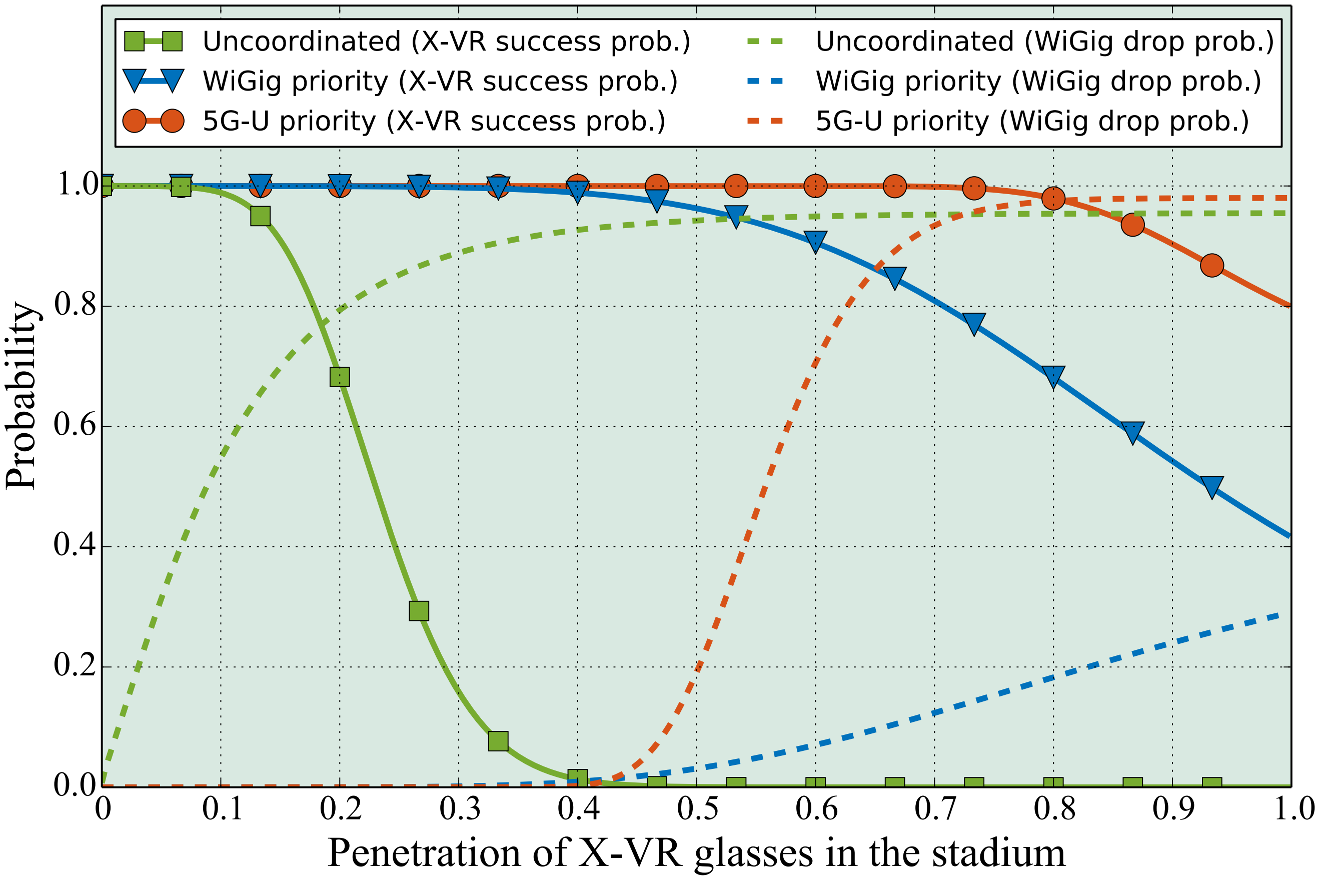

Fig. 4. Effects of X-VR gear penetration in the stadium.

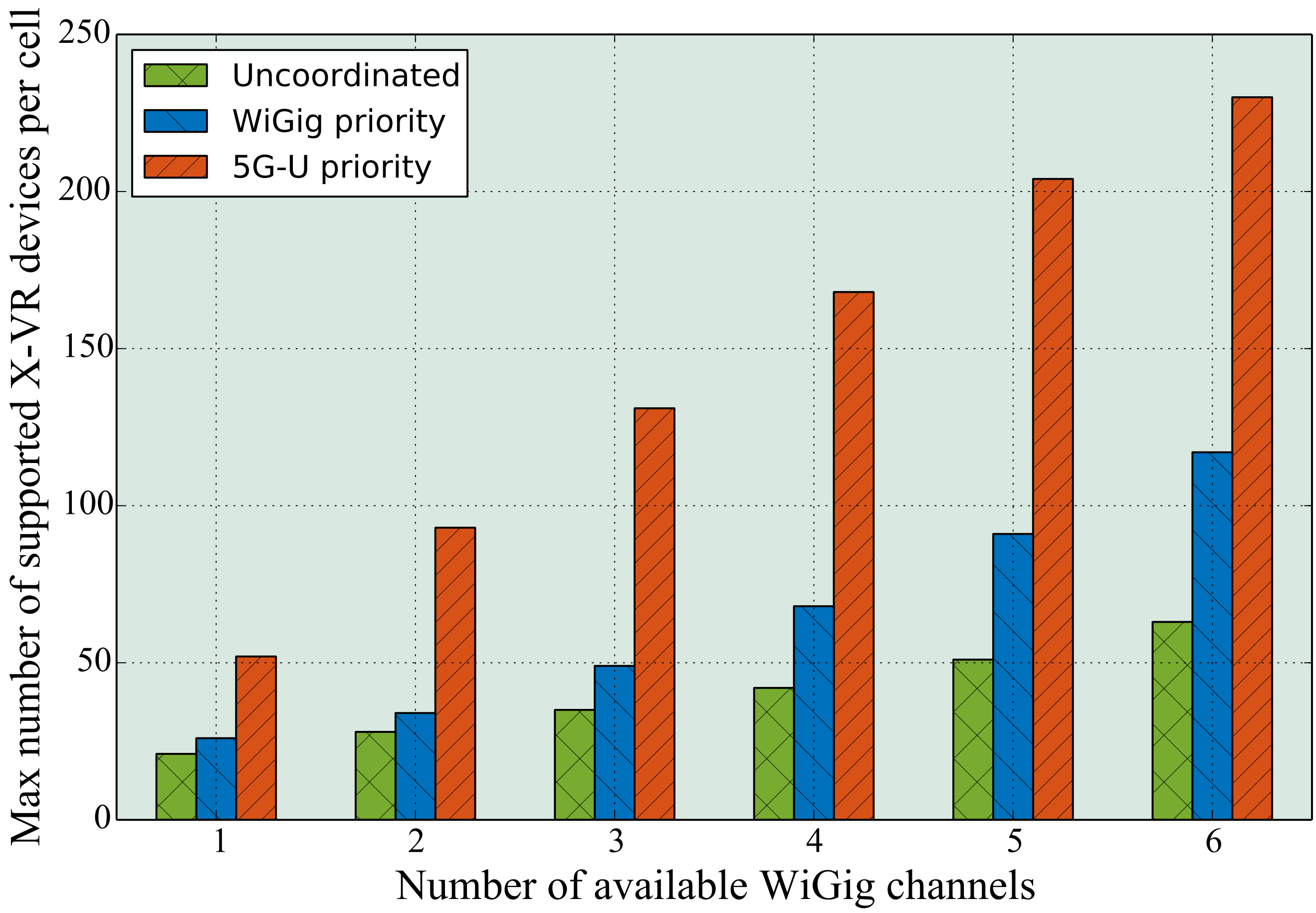

Fig. 5. Effects of the number of occupied WiGig channels.