Ultrareliable and Low-Latency Communication Techniques for Tactile Internet Services

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Abstract—This paper presents novel Ultrareliable and low-latency communication (URLLC) techniques for URLLC services, such as Tactile Internet services. Among typical use-cases of URLLC services are tele-operation, immersive virtual reality, cooperative automated driving, and so on. In such URLLC services, new kinds of traffic such as haptic information including kinesthetic information and tactile information need to be delivered in addition to high-quality video and audio traffic in traditional multimedia services. Further, such a variety of traffic has various characteristics in terms of packet sizes and data rates with a variety of requirements of latency and reliability. Furthermore, some traffic may occur in a sporadic manner but require reliable delivery of packets of medium to large sizes within a low latency, which is not supported by current state-of-the-art wireless communication systems and is very challenging for future wireless communication systems. Thus, to meet such a variety of tight traffic requirements in a wireless communication system, novel technologies from the physical layer to the network layer need to be devised. In this paper, some novel physical layer technologies such as waveform multiplexing, multiple access scheme, channel code design, synchronization, and full-duplex transmission for spectrally-efficient URLLC are introduced. In addition, a novel performance evaluation approach, which combines a ray-tracing tool and system-level simulation, is suggested for evaluating the performance of the proposed schemes. Simulation results show the feasibility of the proposed schemes providing realistic URLLC services in realistic geographical environments, which encourages further efforts to substantiate the proposed work.

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1 Readers are invited to visit https://www.dropbox.com/s/8qnjza9g2h4e/tactile-2017-sls-implementation.mp4?dl=0 for a video clip introducing the proposed work.

I. INTRODUCTION

OWING to continuously increasing demands for new vertical services, academia and industry have been placing a huge emphasis on developing the fifth generation (5G) enabling technologies. According to the international mobile telecommunication (IMT) vision for 2020 [1], emerging 5G services include enhanced mobile broadband services, massive Internet of Things (IoT), and Ultrareliable and low-latency communication (URLLC) services, such as Tactile Internet service. Among them, URLLC services are considered as the most challenging applications in 5G or future cellular systems, and their typical use cases include collaborative automated cars, tele-operations, interpersonal communications (ICs), and immersive virtual reality (IVR) services [2–6].

Unlike the classical high-quality multimedia streaming service, in which high-rate information flows from a source to a sink, sensing information, control and command information, and feedback information that occurred by the actuation according to the control and command form a loop for an information flow in typical URLLC services. In a typical tele-surgery example [9], [10], a real-time high-quality video sensing information of the affected area of a patient needs to be delivered to a surgeon and the surgeon controls a remote surgical robot, wherein elaborate kinesthetic information of the surgeon’s hands and fingers needs to be delivered to the robot; the force and tactile sensing information that occurred from the interaction between the robot and the affected area needs to be fed back to help the surgeon along with the video sensing information. Note that such a typical information flow requires a delivery of high-rate information up to several hundred megabits per second (Mbps) with and end-to-end latency as low as 1 ms and a reliability as high as 99.9999999% (i.e., packet error rate of 10−9), which reveals some challenging aspects of developing URLLC enabling technologies in cellular communication systems.

Studies on typical URLLC use-cases have been carried out, in which typical traffic characteristics and quality of service (QoS) requirements of some URLLC use-cases are reported. In [2], a tele-surgery use case is described in which audio, video, and haptic information needs to be delivered within an end-to-end latency as low as 1 ms and with an extremely high reliability (block error rate (BLER) down to 10−9). In [3], intelligent transportation examples are described, such as
cooperative collision avoidance and high-density platooning, in which sensing information needs to be exchanged within an end-to-end latency as low as 5 ms and with high reliability (frame error rate (FER) down to $10^{-9}$). Further, in [4]–[6], industry automation examples are described, such as time-critical process optimization inside factory and remote control, in which video, audio, and haptic information needs to be delivered within a sub millisecond end-to-end latency and with an extremely high reliability (BLER down to $10^{-9}$). Recently, the IEEE standardization activity on Tactile Internet (IEEE P1918.1) was launched, in which Tactile Internet architecture, functional entities, and various use-cases have been investigated. In [7], [8], detailed traffic characteristics of video, audio, and haptic information such as packet size, arrival rate, and arrival model with QoS such as latency and reliability requirements are described. These examples and scenarios show that traffic characteristics of typical URLLC services can be quite various in terms of their packet sizes and arrival models and their QoS requirements can be quite extreme [11], [12]; therefore, these aspects should be taken into account when developing URLLC techniques.

To support such low-latency requirements of URLLC services, studies in the 3rd Generation Partnership Project (3GPP) on the current long-term evolution (LTE) systems have been performed [13], in which typical downlink (DL)/uplink (UL) radio access and handover latencies are reported as 17/7.5 ms and 50 ms, respectively, and the transmit-time-interval (TTI) reduction, processing time reduction, semi-persistent scheduling, and grant-free access are enumerated as possible remedies. In addition, many technical aspects in the cellular network, including waveform numerology such as symbol length and subcarrier spacing, frame structure, multiple access scheme, pilot design, link adaptation strategy, and scheduling policy need to be designed carefully for URLLC [14]–[16]. 3GPP is standardizing a new radio interface for 5G as the new radio (NR), aiming to reduce DL/UL radio access latency to 0.5 ms [17]. In [18], [19], scalable subcarrier spacing parameters for shorter orthogonal frequency division multiplexing (OFDM) symbol length and mini-slots comprised of various number of OFDM symbols (1-13) are adopted for implementing short TTIs. Further, various ideas on URLLC and enhanced mobile broadband (eMBB) multiplexing for efficient resource utilization [20]–[22] and various ideas on two-way grant-based and grant-free multiple access proposals [23]–[25] to reduce the uplink protocol latency have been discussed. However, such simple suggestions on providing low-latency protocols and frame structures should be just the beginning, as practical URLLC services need a simultaneous provision of low-latency and ultra-reliability with high spectral efficiency, which is very challenging.

In a cellular system, the channel impulse (or frequency) responses of wireless fading channels are not fully predictable and the fluctuation on the received signal-to-noise-plus-interference ratio (SINR) is one of the most challenging aspects for reliable information delivery. The current 3GPP long-term evolution (LTE) employs an appropriate scheduling to utilize multuser diversity, adaptive modulation and coding (AMC) according to channel quality information measured at a receiver, and hybrid automatic repeat and request (HARQ) for an efficient retransmission to provide high reliability as well as high spectral efficiency [26]. However, such an approach requires delays for channel quality measure and feedback, scheduling, and retransmission that it becomes inappropriate for delivering highly latency-sensitive information, although it is the most efficient way to deliver latency-insensitive information. Although some diversity schemes and fast HARQ schemes for better reliability at a low-latency are considered, such as in [27]–[29], their reliability levels and the resulting spectral efficiencies are far from what is required for practical URLLC services. Further, the design of the physical (PHY) layer and medium access control (MAC) layer technologies for URLLC need to consider the variety of different traffic characteristics and the QoS of URLLC services.

Since 2015, the authors had formed a joint URLLC research team and focused on developing spectrally-efficient protocol and multiple access technologies that guarantee both tight low-latency and ultra-reliability requirements for URLLC. To provide ultra-reliability, a large amount of diversity obtained from large degrees of freedom is essential, especially without either instantaneous channel quality feedback or retransmissions in fading channels. Thus, considering a large-scale antenna system (LSAS) (or massive multiple-input multiple-output (MIMO) system) is a natural consequence [30], [31]. In this paper, some novel multiple access schemes for URLLC based on the LSAS are introduced and waveform multiplexing and full-duplex communication techniques are also introduced to further enhance the spectral efficiency and reduce the latency. In addition, a new evaluation methodology is introduced by combining a system-level simulator and a ray-tracing tool with digital maps on real environments and the performance evaluation results are provided.

II. SOME USE CASES AND TRAFFIC REQUIREMENTS FOR TACTILE INTERNET SERVICES

A. Some Use Cases

1) Immersive Virtual Reality: The immersive virtual reality (IVR) technology allows people to use their senses to interact with virtual entities in remote or virtually created environments such that they can perceive all five senses when they are in such remote or virtual environments [8]. Because of its interaction capability beyond the physical limitation, it has been drawing great interest in industries such as gaming, education, and health care [33].

Among the five senses, the vision, sound, and touch senses represent the primary focus and their traffic types and characteristics can be categorized according to each sense. For vision sensing, since the motion-to-photon latency should be within 10-20 ms, the allowed air latency ranges from sub milliseconds to a few milliseconds [6], [34]. Further, considering the field of view, it be it in three dimensions, or extremely high definition (32K) [35], a required data rate for vision information would be in the range between 10 Mbps to 1 Gbps with 99.99%-99.999% reliability. For audio sensing, the audio information includes not only high-fidelity sound but also considerations for three-dimensional head rotations. For touch sensing, haptic
information exchange is required, in which tactile information comprising several bytes for each degree of freedom (DoF) \[8\] times the number of DoFs (i.e., the number of touch spots) up to thousands and the kinesthetic information comprising several bytes per each DoF \[8\] times the number of DoFs (i.e., the number of joints in the human body) up to hundreds with 99.99% reliability.

2) **Tele-operation**: Tele-operations, such as tele-surgery, tele-maintenance, and tele-soccer using remote robotic avatars, allow people to control slave devices such as robots in distant or inaccessible environments to perform complex tasks \[8\], \[36\]. The exchange of haptic information, such as force, torque, velocity, vibration, touch, and pressure, is required between the master and slave devices, and the delivery of high-quality video and audio information is required from the slave devices to the master devices \[8\].

The required data rates and latency requirements of the traffic for tele-operation vary according to the required control precisions for slave devices and the dynamics of remote environments where the slave devices are placed. In a highly dynamic environment such as the one reported in \[37\], haptic information exchange should be within a few milliseconds such that the allowed air latency can be less than or equal to one millisecond with high reliability. Further, for applications requiring extremely high control precision such as in \[9\], \[10\], the delivery of very high-rate video information and the exchange of delicate haptic information with reliability higher than 99.99% is required. Further, for remote skill training such as in \[38\], the number of DoFs can be hundreds to thousands.

3) **Automotive and Internet of Drones (IoD)**: Future cars need connectivity with the infrastructure and other cars for collaborative autonomous driving and in-car entertainments \[3\]. Therefore, a large amount of sensing information needs to be exchanged in a very low latency. Similar to tele-operation applications, the required latency depends on the dynamics of neighboring environments such that the allowed air latency can be less than or equal to one millisecond with high reliability. In addition, for collaborative autonomous driving using artificial intelligence, high-quality video and audio information exchange with high reliability among neighboring cars may be required. In remote driving, haptic information exchange with DoFs up to several tens to hundreds may be required \[8\].

Applications using unmanned aerial vehicles (UAVs), such as drones, are also emerging and among them are drones for public safety, remote explorations, logistics, flying base stations, etc. \[8\], \[39\]. Owing to the high dynamics in such UAV environments, real-time video, audio, and haptic information should be exchanged within a low latency, i.e., the allowed air latency less than or equal to one millisecond for kinesthetic information and a few milliseconds to tens of milliseconds for high-quality video/audio information and haptic information.

4) **Interpersonal Communication**: Interpersonal communication (IC) supports the co-presence of distant users for social development or emotional interaction, and haptic IC (HIC) can deliver human touch as well, allowing for promising applications such as social networking, gaming, education, and training \[8\], \[40\], \[41\].

High-quality video and audio information exchange is required with high reliability, similar to the IVR case, and haptic information exchange is also required. In static dialoguing, a low latency is required for the highly dynamic interaction of haptic information such that the allowed air latency can be as low as a few milliseconds \[8\].

**TABLE I**

Typical Traffic Characteristics and QoS for Some Use-cases

| Application | Types | Reliability (R) | Typical Air-latency (L) | Burst size (B) | Arrival model (A) |
|-------------|-------|----------------|-------------------------|-------------|-----------------|
| **IVR**     | Haptics | > 99.99%       | 0.5-2 ms                | 2-8 B/DoF   | (1/10/100/1000 DoFs) |
|             | Video  | > 99.99%       | 0.5-2 ms                | 1-30 KB     | 100-1000 pkt/s (P) |
| **Tele-operation** | Haptics | > 99.99%       | 0.5-2 ms (high-dynamic) | 2-8 B/DoF   | (1/10/100/1000 DoFs) |
|             | Video  | > 99.99%       | 10 ms (dynamic)         | 1-10 KB     | 100-1000 pkt/s (P) |
| **Automotive** | Haptics | > 99.99%       | 0.5-2 ms (life-critical)| 2-8 B/DoF   | (1/10/100/1000 DoFs) |
|             | Sensor | > 99.99%       | 10 ms (dynamic)         | 1-5 KB      | 100-1000 pkt/s (E) |
|             | Audio  | > 99.99%       | 10 ms (static)          | 1-10 KB     | 100-1000 pkt/s (P) |
| **IoD**     | Haptics | > 99.99%       | 0.5-2 ms (kinesthetic)  | 2-8 B/DoF   | (1/10/100/1000 DoFs) |
|             | Sensor | > 99.99%       | 10 ms (tactile)         | 2-8 B/DoF   | (1/10/100/1000 DoFs) |
|             | Audio  | > 99.99%       | 10 ms (static)          | 2-8 B/DoF   | (1/10/100/1000 DoFs) |
| **HIC**     | Haptics | > 99.99%       | 1-2 ms (interaction)    | 2-8 B/DoF   | (1/10/100/1000 DoFs) |
|             | Video  | > 99.99%       | 10-100 ms (observation) | 2-8 B/DoF   | (1/10/100/1000 DoFs) |
|             | Audio  | > 99.99%       | 5 ms                    | 2-8 B/DoF   | (1/10/100/1000 DoFs) |

1 w/o compression, P: Periodic 2 w/ compression, GE: Gilbert-Elliot (such as in \[32\]) 3 E: Event-driven (Sporadic)
B. Traffic Classification

In Table II, typical traffic characteristics of the use-cases in Section II-A are summarized, in which the traffic characteristics and QoS are represented by the typical air latency, target reliability, packet size, packet arrival rate and model. Here, the baseline of the traffic characteristics and QoS come from [8] but it is further assumed that typical air-latency requirements are set to 20% of the corresponding end-to-end latency requirements and more DoFs and larger packet sizes up to ten times are expected in near future.

The current state-of-the-art cellular communication technology can support various traffic with different characteristics and QoS with good reliability and high spectral efficiency if the required latency is not so tight by controlling the radio resource control (RRC) connectivity of each user according to its activity, scheduling active users with good channel quality, AMC according to its channel quality, and retransmissions using HARQ. However, extremely low latency and high reliability requirements of URLLC services necessitate classifying such traffic and operating different protocols and multiple access strategies according to different target latency and reliability levels. Further, traffic characteristics such as the arrival model and rate also need to be taken into account to design such protocols and multiple access strategies.

First, traffic with loose latency requirements (i.e., \(L > 50\) ms) can be easily supported using a legacy strategy: radio-resource efficient LTE-style four-way RRC connection, scheduling, AMC, and HARQ regardless of traffic type, data rate, arrival model, and target reliability level. In this case, it is not difficult to satisfy the latency and reliability requirements and a higher spectral efficiency is of the most interest. When a latency requirement is slightly tight (i.e., \(L\) is approximately tens of milliseconds), it is better to deal with such packets differently from those with loose latency requirements. Some good approaches include reducing the number of handshakes in the RRC connection protocol as in [23], [24] and shortening the TTI as in [18], [19]. As the target latency is not so tight, it is possible to apply a grant-based multiple access with a radio resource management and a few retransmission can be allowed to guarantee the reliability requirement.

As the latency requirement becomes tighter (i.e., \(L\) is approximately several milliseconds), more elaborately designed techniques need to be applied and the traffic arrival model becomes important. For periodically generated packets, a semi-persistent scheduling can be applied to reserve the radio resources for such packets. Further, at least one or two retransmissions may be allowed such that a reliability requirement can be met with an LTE-style spectrally efficient radio resource management. However, in cases of bursty or sporadically generated packets, a grant-free multiple access, similar as in [42], is necessary and it is important to guarantee a target reliability, which is very challenging. As users can transmit without any grant, the number of users sharing the same radio resources (i.e., a subchannel) varies and it becomes worse if traffic with different characteristics and QoS (such as packet size and target reliability level) are allocated in the same subchannel of a multiple access scheme. In addition, as the latency requirement becomes extremely tight (i.e., \(L\) is less than or equal to 1 ms), retransmission may not be allowed and it becomes very difficult to satisfy a reliability requirement at a reasonable spectral efficiency. A good approach is to classify traffic classes according to the characteristics and QoS such that packets with similar characteristics and QoS are allocated in each subchannel of a multiple access scheme.

In Table II traffic in Table I is classified as an example, mainly according to the latency and reliability requirements, as discussed in paragraphs above. Here, the first row represents a class with loose latency requirements, the second row represents a class with medium latency requirements, and the third row represents a class with low latency requirements but the packets are generated periodically. The other five classes represent very low latency requirements with bursty or sporadic packet arrival characteristics. As they need to be served using a grant-free multiple access, those packets should be further classified according to latency, reliability requirements, and packet sizes so that traffic with similar characteristics are allocated to a subchannel for a reasonable spectrally-efficient radio resource management.

### III. Multiple Access Strategy for URLLC

In Section II typical URLLC use-cases and traffic characteristics are introduced, which necessitate the development of not only a new frame structure with short TTIs and protocol concepts such as in [17]–[19], but also elaborately designed strategies for user RRC state control, radio resource management and optimization, and novel multiple access techniques.
each suitable for the various traffic characteristics and QoS of URLLC services.

In this section, a new user RRC control strategy is suggested with new states for serving traffic with low-latency requirements and the corresponding RRC connection protocols are suggested, in which different levels of protocol procedures, core network connection strategies, and radio resource allocation strategies are provided according to the traffic classes of URLLC users. In addition, DL and UL radio resources are appropriately partitioned to support different multiple access schemes, where each multiple access component handles traffic with similar characteristics and QoS for better spectral efficiency. To provide a high-level of reliability even in cases of extremely low latency requirements, an LSAS is assumed for a base station and a latency-optimal resource management scheme is suggested. According to each user’s RRC state, a different level of radio resource allocation is provided to enhance the spectral efficiency while guaranteeing the latency and reliability requirements.

A. RRC Connection Protocols

Recently, in the 3GPP standardization for NR, a new user RRC state, RRC_INACTIVE, has been defined [43]–[45]. According to a general description in [46], RRC_INACTIVE is different from RRC_IDLE in that a user keeps the previous configuration information when suspended from RRC_CONNECTED, so that it can resume RRC connectivity without a long delay. Further, from a core network’s perspective, the RRC_INACTIVE and RRC_CONNECTED are the same because core network is connected (i.e., CN_CONNECTED) in both cases. If the RRC connectivity is lost, a user needs to perform the RRC connection setup similarly from RRC_IDLE.

In this paper, such a new state is further classified into two different states according to the required number of handshakes between base stations and users and their levels of allocated radio resources. As shown in Fig. 1 two new states, RRC_INACTIVE and RRC_INACTIVE_CONNECTED are introduced. Here, from a core network’s perspective, both states are the same to the RRC_CONNECTED. To a user in RRC_INACTIVE or RRC_INACTIVE_CONNECTED, preambles are allocated as dedicated radio resources in addition to the RRC configuration information and they uniquely indicate each user’s identity and intended traffic classes. Furthermore, to each traffic class of each user in RRC_INACTIVE_CONNECTED, the subchannel for possible UL transmissions is allocated as a shared resource. Here, traffic classes for each service are assumed to be registered at the initial service negotiation and RRC connection stage (i.e., admission). If some traffic classes of a user require medium to low latency (for example, Class 2 in Table II), then the user can utilize the RRC_INACTIVE state, in which the allocated preambles indicating the user identity and each of the traffic classes with such latency requirements enable a fast RRC connection setup once a packet of such classes arrives. In addition, if some traffic classes of a user require very low latency (for example, Class 6 in Table II), the user can utilize the RRC_INACTIVE_CONNECTED state, where the allocated subchannel and user-specific preamble for each of such traffic classes enable immediate RRC connection resuming as soon as a packet of such a class arrives.

The discussion above on the proposed RRC state transition can be re-drawn in a protocol perspective in Fig. 2. Here, three protocols for the RRC connection are presented, in which the first one represents an LTE-style four-way handshaking RRC connection procedure, and the second one represents a two-way handshaking RRC connection procedure for providing a fast-grant multiple access (FGMA), and the last one represents an immediate RRC connection for providing a grant-free multiple access (GFMA).

The first protocol is for traffic classes with loose latency requirements, such as in the first row in Table II. The LTE-style four-way handshaking using a cell-specific common set of preambles is spectrally-efficient and the LTE-style granted access is performed in the UL. However, as the latency becomes slightly tight, the delay caused by a grant procedure needs to be reduced and sending a scheduling request after a

![RRC state transition diagram](image-url)
(sporadic or bursty) packet arrival is enough to obtain a grant for intended packets since a unique preamble indicating the user identity and the intended traffic class identity is already allocated and used in the scheduling request so that a base station performs a scheduling for the reliable delivery of such packets immediately and sends a grant with the allocated subchannel information. This protocol and FGMA is suitable for traffic with medium latency requirements as in the second row in Table II and traffic with low latency requirements but periodic arrival characteristics as in the third row in Table II so that a semi-persistent scheduling and subchannel allocation can be used.

For traffic with low latency requirements, the protocols above may not be used and an immediate packet transmission is required in the UL as soon as a packet of such a class arrives. In this case, the third protocol for GFMA is suggested, in which a subchannel as a shared resource and a user-specific preamble as a dedicated resource are already allocated for each traffic class with a low latency requirement and used for an immediate packet transmission as soon as a packet arrives. The GFMA with such a protocol is suitable for traffic with low latency requirements as in the fourth to eighth rows in Table II.
Maximized System SE of given pilot length

Maximized SINR in data phase

Optimize resource (subchannel allocation portion)

Optimize scheduling group

Optimize subchannel structure

Long-term CSI and Energy information of UEs

Make grouping candidates for all possible pilot length

Optimize transmit power (pilot and data phase)

# of UEs per subchannel

Subchannel length N

Data length N - θ

Pilot

(b) Latency-optimal radio resource management and optimal frame configuration

User identity

0 0 1 0 … 1 1

Traffic class identity

Preamble Grant Pilot Data

Processing delay (BS)

Processing delay (UE)

Preamble Allocation

Chu Sequence Generator

Fig. 4. Optimal radio resource management strategy for FGMA satisfying latency and reliability requirements.

Table I

To employ such different multiple access schemes in a single carrier, the DL and UL radio resources are partitioned as shown in Fig. 5. For each service of each user, traffic is classified according to traffic characteristics and QoS as described in Section II and traffic of multiple users with similar characteristics and QoS are grouped and served together in each multiple access. Although different procedures for the RRC connection and the corresponding multiple access concepts are proposed to support various latency requirements required for URLLC services, providing reliability at a reasonably high spectral efficiency is still quite challenging. One good approach is to make the traffic requirements and QoS of multiple users in each FGMA or GFMA component as similar as possible and it can facilitate designing a radio resource management for reliability and high spectral efficiency [47].

B. Multiple Access with Latency-Optimal Radio Resource Management

Reliable information delivery in a cellular communication environment has been challenging because of channel quality fluctuation caused by the wireless fading channel and mobility. Although a low level of reliability could be provided by exploiting a limited order of diversity in time, frequency, and space in legacy cellular communications (the second generation or the earlier-stage third generation), the LTE has been successful in providing a high level of reliability primarily by using AMC based on channel quality information measurement and feedback and retransmissions using HARQ [26].

However for URLLC services, a low latency requirement may restrict the use of AMC and HARQ or at least allow them only in a very limited manner so that most of the reliability part needs to be resorted on diversity again. Although classical repetition approaches can be adopted in time, frequency, or even multiple communication interfaces can be used [48], spectral efficiency may be significantly degraded, especially as more URLLC services are served. Thus, better approaches without significant spectral efficiency degradation are preferred and the most promising solution is to employ a large number of antennas at a base station, i.e., LSAS.

Once an LSAS is assumed, the channel fluctuation caused by the wireless fading channel and mobility can be overcome (or significantly reduced at least) because of the channel hardening effect [49]. However, the challenge is on the radio resource optimization in which preamble overhead, channel estimation quality, and user grouping are jointly considered and optimized. In [47], the authors proposed a latency-optimal semi-persistent scheduling algorithm for an LSAS, which can be utilized for guaranteed reliability in FGMA or GFMA.

For FGMA, a unique preamble indicating the user identity and traffic class identity, as shown in Fig. 4(a), is allocated to each traffic class for each user during the admission control process. As the traffic characteristics and QoS of an arrived packet of each user, such as packet size, arrival model and rate, and latency and reliability requirements, can be detected at a base station from the preamble sent during its scheduling request, the base station can group users with similar traffic characteristics and QoS and apply the latency-optimal scheduling algorithm in [47]. As shown in Fig. 4(b) the transmit power of each user is first optimized based on the long-term channel state information and energy information of each user and then optimal user grouping is performed in which each user group shares a subchannel. From the optimization results, the pilot overhead for each subchannel is semi-persistent scheduling algorithm for an LSAS, which can be utilized for guaranteed reliability in FGMA or GFMA.

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Fig. 4. Optimal radio resource management strategy for FGMA satisfying latency and reliability requirements.
latency requirements is determined. Subsequently, the sub-channel construction and allocation information is delivered in a resource grant. Therefore, the proposed FGMA with a latency-optimal radio resource management can maximize the spectral efficiency while guaranteeing latency and reliability requirements for URLLC services.

In GFMA, the challenge for guaranteed reliability is even more difficult because each user transmits its packet as soon as it arrives without any grant. However, employing an LSAS can also reduce such an uncertainty in addition to the channel hardening effect reducing the uncertainty in channel quality and it is possible to modify the algorithm in [47] by considering such uncertainties together as indicated in Fig. 5. As traffic with similar characteristics and QoS is already grouped at the admission control stage, a base station is aware of the arrival model and rate of each user so that it can be aware of the statistics for the actual transmitting users in each user group candidate. Thus, the base station can determine the optimal scheduling by considering such statistics of the user grouping candidates [42], [50]. At the base station receiver, user detection needs to be first performed using preambles and the user detection capability should provide a success probability higher than the required reliability level, which is also considered in the optimization process [42], [50]. Simulation results in [42], [50] showed that the required radio resource for GFMA does not increase significantly compared with the case of a granted multiple access such that the proposed protocol and GFMA with a latency-optimal radio resource management can maximize the spectral efficiency while guaranteeing latency and reliability requirements for URLLC services.

**IV. MORE PHY TECHNOLOGIES**

In the previous section, a set of multiple access techniques have been introduced, in which i) data packets for URLLC services are classified according to their traffic characteristics, including packet size and arrival statistics, and their latency and reliability requirements, ii) radio resources are partitioned to multiplex different multiple access components simultaneously, iii) each user or base-station is equipped with as many queues as its number of different packet classes, and iv) each multiple access supports its own packet class of multiple users. By virtue of the large number of antennas and the latency-optimal scheduling, the latency and reliability requirements of each packet class can be simultaneously satisfied.

However, to realize such a concept, the radio resource needs to be well partitioned in a waveform level with good synchronization strategy. Moreover, to maximize the spectral efficiency, it is desired to use waveforms not only matched to user environment (i.e., delay spread and mobility) similar to the numerology multiplexing concept [51], but also appropriate for the latency requirements of users because the latency caused by the filters in a transceiver can be critical for packets with extremely low latency requirements. Thus, to devise a waveform multiplexing is a natural consequence, in which different types of waveforms (i.e., filtered-OFDM, generalized frequency division multiplexing (GFDM), etc) each with different numerologies (cyclic prefix length, subcarrier spacing, filter length, etc) are multiplexed.

In a latency budget such as in [13], one important component is the processing delay and most of the processing delay comes from the channel encoding/decoding latency.
Thus, it is very important to devise channel codes with low encoding/decoding latency. In addition, such channel codes should have good performance in a high-reliability regime (i.e., frame error rate (FER) in the range of $10^{-3}$ to $10^{-7}$) such that both the waterfall performance and the error floor performance need to be considered.

To further improve the spectral efficiency and reduce the delay between the DL and UL, the best method is to adopt full duplex communication and the corresponding frame structure. Since an LSAS is assumed, a channel reciprocity such as in time division duplexing (TDD) is required for efficient channel estimations. However, in TDD, the delay between UL and DL subframes (or (mini) slots) may cause a latency problem. Thus, a practically feasible full duplex cellular communication technique can provide not only almost double the spectral efficiency but also a reduced delay between UL and DL as in frequency division duplexing (FDD). Although the feasibility for self-interference cancellation (SIC) at a (low-power) base station has been confirmed [53], [54], the interference at DL users caused from UL users needs to be avoided. Although a full-duplex cellular communication can work if an appropriate paring of DL/UL users is assumed [55], better interference avoidance scheme needs to be devised for incorporation with various scheduling strategies without such pairings.

### A. Waveform Multiplexing

To multiplex different classes of services in a common carrier, one approach is to multiplex URLLC packets on eMBB resources, such as in [21], and the other is a numerology multiplexing by resource partitioning, such as in [20], where different numerologies for OFDM parameters and frame structure can coexist. Owing to the capability of selecting the appropriate numerologies according to the users’ environments and service requirements, a numerology multiplexing is considered as a promising solution. However, inter-numerology interference needs to be taken into account and an appropriate filter design for low out-of-band-emission (OOBE) is required [56].

As an elegant solution to implement such a numerology multiplexing concept, a waveform multiplexing system is proposed in [52] as illustrated in Fig. 6 and it employs scalable subcarrier spacings and dynamic cyclic prefix (CP) management. The proposed waveform multiplexing selects not only appropriate subcarrier spacings and CP lengths according to users’ channel environment and mobility but also waveform filters for minimum guard bands according to service (latency) requirements and OOBE levels.

In the proposed waveform multiplexing, users with similar mobility (channel coherence time), delay spread, and latency requirements are grouped and the appropriate subcarrier spacing and CP length are selected for each group to minimize the CP overhead. For each group, an appropriate waveform filter is determined to minimize the guard band while satisfying latency requirements. In cases where a low OOBE level is desired and latency requirement is loose, waveforms with very low OOBE, such as in [57]–[59], can be used to enhance the frequency-domain SINR. However, in cases where an extremely low latency is required, waveforms with short filter delays at a reasonable OOBE, such as in [60], [61], may be preferred. Such a waveform multiplexing concept can be considered a generalization of numerology multiplexing in a single waveform, such as in [57], [62].

### B. Synchronization Issue

In the DL, each user can employ a legacy time and frequency synchronization, such as in [67], [68], on the subbands where it belongs to, even in cases of employing a waveform multiplexing with different numerologies and waveform filters. Thus, synchronization for DL does not raise a new critical issue and can be done similarly as in the LTE.
In the UL, it is reasonable to assume a similar closed-loop procedure for a strict time synchronization as in the LTE for eMBB and URLLC services. However, since higher mobility and higher frequency bands need to be supported, especially for URLLC services, time synchronization errors and frequency offsets due to Doppler shifts may cause non-negligible performance degradation, especially for URLLC services in which high reliability is required and sporadic access needs to be supported. As a remedy, an interference cancellation approach is adopted at the base-station receiver as illustrated in Fig. 7(a). Here, different time and frequency offsets of multiple users are assumed to be estimated similarly as in [69], [70] along with a closed-loop time synchronization as in the LTE. In order to reduce multiple user interference caused from time and frequency offsets of multiple users which may be caused from high mobility, high frequency, or sporadic access, an elaborately designed receiver filter is applied to maximize the signal-to-interference ratio (SIR) of users by using the estimated time and frequency offsets and it is shown in [63], [64] that the proposed approach can provide better performance compared to those in [71], [72] as shown in Fig. 7(b).

C. Channel codes for URLLC

Recently, low-density parity check (LDPC) codes have been adopted for eMBB services in the NR standard [73]. Such LDPC codes can be considered as raptor-like quasi-cyclic LDPC (QC-LDPC) codes and they can provide near-optimal waterfall performance as well as efficient encoding and decoding implementation methods such that they are quite appropriate for eMBB applications. However, their error floor performance may not be good, especially as the code rate decreases, because of the lack of linear minimum distance growth (LMDG) property and too many degree-1 variable nodes, as expected in [74], and it may limit the use of such protograph-based raptor-like (PBRL) QC-LDPC codes.

Fig. 7. UL receiver structure for handling synchronization issue [63], [64].

(a) Protograph structure of an ARACA code and performance comparison [65], [66].

(b) Required SNRs for target FERs.
for URLLC applications, especially for the cases where the required reliability is quite high (e.g., FER in the range of $10^{-3}$ to $10^{-7}$) and the latency requirement is tight such that a retransmission is not allowed.

In [65], accumulate repeat accumulate check accumulate (ARACA) codes are recently proposed by the authors to provide high reliability by having both the LMDG property (i.e., no error floor) and good water-fall performance with an efficient encoding structure. Fig. 8(a) shows the protograph structure of an ARACA code, which is comprised of the two outer code parts (o1 and o2) and the two inner code parts (i1 and i2) as described in [65], and it is characterized by the outer connections that can provide an efficient low-complexity encoding similar to an accumulate repeat accumulate code [75] as well as the LMDG property with a water-fall performance similar to an accumulate repeat jagged accumulate code [76]. Further, Fig. 8(b) shows the good performance of rate-compatible ARACA codes [66] compared with PBRL QC-LDPC codes in [77]–[79]. In addition, [80] proposes a low-latency and low-complexity layered Richardson-Urbanke encoding method and encoder structure as well as a low-latency and low-complexity big-layer parallel decoding method and decoder structure, which shows that the proposed ARACA codes are promising for URLLC services.

D. Full-duplex Cellular Communication: code-division duplexing spatial-division multiple access (CDD-SDMA)

In a full-duplex cellular communication, DL users suffer from the interference caused by UL users as illustrated in Fig. 9(a). As a result, without an elaborate management of such interference, the overall performance, such as the rate distribution of users, cannot be meaningfully improved, even in cases where perfect SIC is assumed at a base station.

As a remedy, a novel CDD-SDMA is proposed, in which UL interferences are aligned to a null space orthogonal to the signal subspace for DL multiuser multiple-input multiple output (MU-MIMO) by using orthogonal codes between DL and UL and employing antenna reconfiguration (or different versions of analog beamforming) to align all UL interferences into a single dimension of the DL signal space similarly as in [81] and devising an efficient DL/UL MU-MIMO schemes on the remaining signal subspaces on DL/UL similarly as in [82] with the DoFs approaching that of the normal zero-forcing MU-MIMO in a half-duplex DL/UL.

To confirm the feasibility of the proposed CDD-SDMA, not only a practical indoor hotspot environment and a spatial channel model in [83] are used but also adjacent channel interference and in-band blocking due to the remaining frequency offsets among UL users (< 100Hz) and the finite resolution (12 bits) of analog-to-digital converters as well as co-channel interferences at the same resource block are considered in the case of 40 baseband streams and 100 physical antennas at a base station. As shown in Fig. 9(b), more than 70% improvement in spectral efficiency is expected in a practical environment, even considering such non-ideal effects. Thus, the proposed CDD-SDMA can be considered as a promising solution, not only for almost doubled spectral efficiency but also to significantly reduce the delay between UL and DL while exploiting channel reciprocity.

V. Evaluation Methodology and Simulation Results

Two-dimensional (2D) regular cell layouts with 2D stochastic wireless fading channel models have been widely used to evaluate the performance of legacy cellular systems. As the uses of multiple antennas and small cells become widespread, beam-steering effects according to elevation angles matter and such 2D channel models with a 2D regular cell layouts have evolved into 3D channel models by applying stochastic channel parameters for elevation angles, which include the 3GPP 3D spatial channel model [83] used for evaluating LTE technologies. However, in most LTE system-level simulation
(SLS) scenarios, 2D regular layouts have been commonly used such that the channel parameters between a randomly selected transmitter and receiver pair are primarily dependent on scenario-dependent parameters and the locations of nodes including the two in the desired pair and interfering sources.

As a typical cell size shrinks for an enlarged area spectral efficiency, a cell deployment scenario should consider the geography of a target environment including its landform, shapes and heights of surrounding structures such as buildings, and different attenuation factors due to different constituent materials of each surrounding structure. To exploit such a real geography, map-based channel models utilizing ray-tracing tools have drawn much interest from academia and industry, such as in [84]–[90]. Reasonable agreement with hardware measurements has been reported in [84]–[86], [88], [89], [91] and link-level simulations (LLSs) and SLSs have been performed to evaluate their proposed work by using measurements from hardware testbeds and/or software algorithms in environments similar to real worlds [52], [91]–[99].

Fig. 10 shows the proposed 3D SLS evaluation strategy in this paper for the performance of UL multiple access and DL waveform multiplexing, where a high-resolution digital map is constructed for the GangNam station area (Seoul, Korea), real base station deployment information, such as the locations as well as the antenna heights and tilting angles, are taken into account, and the reported typical user density for each part of the digital map is applied as in [52], [100]. Using such a realistic digital map and the locations for base stations and users, 3D channel parameters are collected [83]–[88], [90], [91]–[99] using the ray-tracing tool called Wireless System Engineering (WiSE) developed by Bell Laboratories [85]. Subsequently, based on the collected data, 3D wireless channels are generated as in [83] according to either a deterministic model based on specific locations of the transmitter and receiver pairs or a stochastic model with statistics matched to this specific environment according to this digital map.

In Fig. 11, the UL latency and spectral efficiency distribution of typically distributed 6000 RRC_INACTIVECONNECTED users are shown when an antenna array with 128 antenna elements is assumed in each of 12 real base stations deployed in the GangNam station area with the same height and tilting angle. Here, the traffic characteristics are assumed as follows: the packet size is 8 KB (64 Kbits), average arrival rate is 100 packets per second, arrival model is a sporadic Poisson random arrival and the latency and reliability constraints are 2 ms and 99.999%, respectively. Here, the CP overhead is assumed to be 25% and variable-length (minimum 0.2 ms) mini-slots comprised of subchannels are assumed for a frame structure. Further, users are associated with the nearest base station and each base station determines the required amount of radio resources (mini-slot length and bandwidth) to support...
grant-free accesses with guaranteed QoS for its associated users, in which user grouping, portion of pilot symbols in each subchannel allocated to each user group, and power control for each user are optimized. Then, the spectral efficiency is evaluated as the ratio of the sum of goodputs (in bps) and the sum of required amount of bandwidth (in Hz) of these cells considering the CP/pilot overhead, channel estimation error, and channel code FER performance. In addition, to evaluate the latency distribution, the required TTI length as well as queuing delay due to a random packet arrival, wireless propagation delay, and decoder processing delay are also taken into account, similarly as in [13], where the queuing delay is assumed to be uniformly distributed over a minimum TTI length and the throughput and latency of the channel decoder at a base station are assumed to be 50 Gbps and equal to the minimum TTI length, respectively.

In Fig. 11(a), the latency distribution of the proposed GFMA is evaluated and compared with the cases where an LTE-style four-way access with a round-robin scheduling and equal power control (denoted as ‘LTE-A Extension’) and the proposed FGMA are instead applied. Here, in addition to the processing delay for decoding, a processing delay for scheduling as long as two times the minimum TTI length is considered in FGMA. Further in Fig. 11(b), the spectral efficiency distribution (for goodput only) of the proposed GFMA is evaluated and compared with the two cases. From the results, it is confirmed that the proposed GFMA is the most efficient for traffic with tight latency requirements and sporadic arrival characteristics. In ‘LTE-Extension’, a large amount of latency budget (more than 80%) is wasted for the 4-way handshaking such that the latency distribution and spectral efficiency distribution for goodput are significantly degraded. In FGMA, although some portion in the latency budget is spent for the two-way handshaking and scheduling, a granted access with a latency-optimal scheduling improves the spectral efficiency during data mini-slots so that these two schemes can provide similar spectral efficiency performance in this specific case. In general, as the latency requirement becomes tighter...
and/or more antennas are equipped at a base station, GFMA performs better than FGMA. Also in Fig. 11(b) the spectral efficiency distribution of GFMA is shown when the packet arrival model changes to be periodic with perfectly aligned arrival times so that a semi-persistent scheduling and resource allocation can be allowed. In this case, GFMA can provide much higher spectral efficiency with guaranteed latency and reliability because the fast protocol of GFMA enables an initial access with guaranteed latency requirement and such initial overhead for the grant becomes ignorable.

In summary, Fig. 11 shows that i) although equipped with a large number of antennas and reduced TTIs, LTE-style RRC connection protocol and multiple access cannot provide sufficiently high reliability and low latency even at a very low spectral efficiency and ii) the proposed GFMA and FGMA can successfully guarantee high reliability and low latency at reasonably high spectral efficiency according to traffic class and QoS.

In addition, Fig. 12 shows the performance gain of employing the proposed waveform multiplexing in DL. Here, to clearly show the advantage of the proposed scheme, a single transmit antenna is instead assumed for each base station. The upper bound (assuming ideally controlled dynamic CP lengths, optimal OFDM parameters and ideal filter characteristics by Genie) on the spectral efficiency distribution of the proposed waveform multiplexing is shown and compared with the case of conventional LTE-based multiband OFDM. Here, the overall performance gain can be as high of 1.67 times, in which the two gains from selecting the ideal waveform on each subband according to OOBEC characteristics and latency requirements and from selecting the optimal CP length and OFDM parameters are both meaningful in a realistic scenario. Although it might be too optimistic, a direct combination of the results in Figs. 9 and 12 with those in Fig. 11 may anticipate that further gains in spectral efficiency with respect to those shown in Fig. 11 (up to 100%) can be obtained by combining waveform multiplexing and CDD-SDMA with the proposed multiple access schemes.

VI. CONCLUSION

In this paper, novel URLLC techniques were introduced for realizing Tactile Internet services in realistic environments. The traffic characteristics and required QoS of typical URLLC (or Tactile Internet) services in literature were summarized and classified from the perspective of designing the PHY and MAC layers of a cellular system. Investigations on typical traffic in typical use-cases justified the necessity of defining new user states and devising protocols for RRC connection according to latency requirements, multiplexing of multiple access schemes over radio resources to meet a variety of different traffic characteristics and QoS of URLLC services, and the development of latency-optimal radio resource management strategies to maximize the spectral efficiency while guaranteeing the latency and reliability requirements.

This paper proposed two additional user states aimed for low latency and devised the corresponding protocols and radio resource allocation strategies in detail. Further, a realistic map-based SLS approach was proposed based on a refined digital map construction, a realistic node distribution scenario, data collection via a ray-tracing tool, and the corresponding deterministic or stochastic 3D channel model. Simulation results showed that the proposed schemes are promising for supporting URLLC services with high spectral efficiency while guaranteeing latency and reliability requirements.

To implement the proposed protocols and multiple access schemes in a spectrally efficient way, more PHY technologies on waveform multiplexing and synchronization strategy, channel codes for low processing delay and high reliability, and a novel DL/UL MU-MIMO concept combining interference alignment for a practical full-duplex cellular communication were further introduced, where each of them can provide significant performance improvement, even when incorporated with others, which encourages further efforts to substantiate the proposed work.

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