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RESEARCH ARTICLE

Radio Resource Management Scheme for URLLC and eMBB Coexistence in a Cell-Less Radio Access Network

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ABSTRACT We address the latency challenges in a high-density and high-load scenario for an ultra-reliable and low-latency communication (URLLC) network which may coexist with enhanced mobile broadband (eMBB) services in the evolving wireless communication networks. We propose a new radio resource management (RRM) scheme consisting of a combination of time domain (TD) and frequency domain (FD) schedulers specific for URLLC and eMBB users. We also develop a user ranking algorithm from a radio unit (RU) perspective, which is employed by the TD scheduler to increase the efficiency of scheduling in terms of resource consumption in large-scale networks. Therefore, the optimized and novel resource scheduling scheme reduces latency for the URLLC users (requesting a URLLC service) in an efficient resource utilization manner to support scenarios with high user density. At the same time, this RRM scheme, while minimizing the latency, it also overcomes another important challenge of eMBB users (requesting an eMBB service), namely the throughput of those who coexist in such highly loaded scenario with URLLC users. The effectiveness of our proposed scheme including time and frequency domain (TD and FD) schedulers is analyzed. Simulation results show that the proposed scheme improves the latency of URLLC users and throughput of the eMBB users compared to the baseline scheme. The proposed scheme has a 29% latency improvement for URLLC and 90% signal-to-interference-plus-noise ratio (SINR) improvement for eMBB users as compared with conventional scheduling policies.

INDEX TERMS Cell-less, radio access network, URLLC, RRM, 5G and beyond networks.

I. INTRODUCTION

Latest fifth generation (5G) wireless communication technology is being deployed all over the world to meet the tremendous demand from the existing diverse networks and services, mainly categorized as enhanced mobile broadband (eMBB), massive machine type communication (mMTC), and ultra reliable low latency communication (URLLC) [1], [2], [3]. However, a vast range of unparalleled and evolving use case scenarios, business models, and vertical applications will also emerge along with the 5G network's ecosystem in the form of coexistence networks of URLLC and eMBB, such as smart meters, smart airports, smart amusement parks, industrial automation, real-time control, augmented reality (AR), virtual reality (VR), smart healthcare systems, intelligent transportation, etc. These emerging applications would cause a scarcity of radio resources due to the need to guarantee the reliability of low latency services simultaneous to the presence of eMBB traffic. In addition, the increasing number of URLLC users from emerging applications creates challenges to state of the art resource allocation.

Recently, a new radio access network (RAN) architecture known as cell-less (or cell-free) [4], [5] is proposed to provide high spectral efficiency, flexible and cost-efficient

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deployment, ensure high quality of service and benefit from low path loss propagation conditions. In the cell-less architecture, the cell boundaries are removed from the user equipment (UE) view point. In most of the recent literature illustrating the advantages of cell-less massive multiple-input-multiple-output (mMIMO) over legacy architectures, the relevant key performance indicators (KPIs) for eMBB service type are used [6]. Furthermore, the analysis in few recent works such as [7] and [8] are conducted over URLLC requirements with short packets. However, they focus on the scenarios with large number of transmitters in comparison to the number of UEs. Hence, they neglect the latency performance degradation in highly loaded scenarios where there is a large number of URLLC UEs. They mainly focus on providing a large number of transmitters to support users, which has a high practical deployment complexity.

A relevant example of scenario with a large number of URLLC users is Smart Metering Networks (SMN). In such types of networks, data collection from many meters or devices and data transmission over long distances need to be enabled. Low latency is a highly demanded requirement which will directly impact the efficiency of smart planning for different types of energy (e.g. gas, electricity, and water). SMN allows people to understand how they are using energy and where they might be able to economize given their usage levels [9], [10]. An efficient low latency and highly reliable data transmission will afford the near real time planning transmission regarding energy consumption and could significantly affect the cost of energy for consumers and providers. In addition to that, it will enable many opportunities for the governments in terms of managing the country's level of energy consumption. Assuming the large number of devices which need to send and receive short packets, with very low latency transmission, the number of resources will be a bottleneck causing a harmful competition. Note that the consumer could also expect to trace the consumption summary to have better experience from SMN. Therefore, a limited number of eMBB devices could be existing in the network as well.

Other representative use cases are smart airports and smart amusement parks which need a low latency smart planning for many devices carrying different services. In these use cases, delivery of such efficient planning with low latency is critical to control the human traffic, service scheduling, etc. Industrial 5G is a promise to support private networks for URLLC service delivery. Big industry players are working to deliver industrial 5G, enabling smart energy protocols and ensuring high private and global digitalization revenues [11], [12].

A. LITERATURE REVIEW

There have been several studies in the literature reporting resource allocation mechanisms enabling coexistence scenarios of URLLC and eMBB [13], [14]. The authors in [13] proposed a resource scheduling scheme by optimizing the bandwidth pre-allocation for eMBB services and minimizing the decoding error rate of the devices carrying URLLC services to meet the needs of the system. Mengge et al. proposed a two-stage resource allocation scheme for eMBB and preference-based URLLC resource preemption schemes for bandwidth-sensitive URLLC and time-sensitive URLLC respectively to improve the reliability of eMBB traffic [14]. The URLLC requirement is characterized by the 3rd generation partnership project (3GPP) as 99.999% reliability with an end to end latency less than 1 ms [15] which is planned to be extended in the new release with additional features, e.g., anything reality, 5G new radio (NR) for high frequency, etc [16]. However, these works do not consider the impact of a higher number of URLLC users for the use cases and applications. Some research efforts have been invested in the context of using the advanced allocation of frequency resources to the eMBB and URLLC services [17], [18], [19]. However, these works exhibit a lower use of frequency resource utilization. To alleviate this limited resource utilization, different frequency resource allocation schemes were proposed in [20], [21], and [22]. These research schemes mostly allocate frequency resources firstly to the eMBB as per throughput demands where some resources are reallocated to URLLC if URLLC traffic comes in the meantime. However, these papers do not reasonably account for the impact of the URLLC devices on eMBB services.

Considering the resource limitations in wireless networks where URLLC and eMBB users might coexist, improving the network performance for each group in a way that does not degrade another group's criteria is an important challenge. The study in [23] tackled the resource allocation problem for a single cell network with eMBB and URLLC services. The authors proposed a deep reinforcement learning (DRL)-based optimization algorithm to solve the problem through the central implementation at the base station (BS). However, the multi-cell scenario was not covered in this paper. In [24], a multi-agent DRL-based algorithm is proposed to solve the problem of eMBB and URLLC scheduling in multi-cell scenarios by taking the advantages of O-RAN architectures in implementing learning algorithms. Inter-cell interference is addressed in many works, such as [25] and [26], using power boosting coordination or sleep mode techniques supporting URLLC services. In the context of inter-cell interference and coexistence of URLLC traffic with eMBB traffic, [27] presented a joint link adaptation and scheduling policy which addressed these challenges. In [28], the authors presented a resource allocation technique based on the risk-sensitive approach for URLLC traffic. The uncertainty of eMBB transmission is considered to be minimized. The conditional value at risk is introduced to estimate the uncertainty of eMBB traffic. Many other works (e.g., [29], [30]) proposed joint scheduling techniques for URLLC and eMBB traffic using approaches like deep supervised learning or preemption-aware subspace projection through time and frequency domain (TD, FD) schedulers.

However, these solutions do not cover scenarios with a large number of URLLC devices. This challenge would become worse for resource allocation in case of highly loaded and massive number of URLLC users in mixed URLLC and eMBB scenarios. This situation introduces a high competition for the resource blocks which tends to increase the latency of the waiting period of the URLLC packet with the increasing number of users, thus hampering the main attributes of URLLC services. In [31], the authors proposed a novel framework, which includes a massive URLLC scheduling technique, the network assisted traffic model, and the quality of service (QOS)-aware congestion avoidance algorithms. The proposed scheduler consists of TD and FD resource allocation. However, the inter-cell interference management is not considered. An attractive centralized RAN (C-RAN)-based multi-cell scheduling algorithm is proposed in [32]. The TD scheduler solves the user association problem centrally, while the FD scheduler performs RB allocation for the users associated with the same cell. However, the FD scheduler does not mitigate the inter-cell interference because of its competitive algorithm for RB allocation. Therefore, throughput performance will be degraded when the number of users increases. It is obvious from the above literature that existing techniques and approaches of the radio resource allocation and management of the 5G systems will not be sufficient to satisfy these emerging and envisaged use cases in the cell-less paradigm, rather it would require to introduce new schemes of radio resource management. In [33], we proposed a sleep mode scheme within a cell-less architecture using cooperative interference management. The proposed interference management technique helps to achieve a stable performance within a cell-less architecture with a large number of users.

Clearly the impact of a high number of URLLC service requests from the envisioned use cases could impose operational challenges on network performances for the coexistence scenarios. However, the above mentioned literature does not reasonably address the challenge of applicability of such solutions in highly loaded scenarios with a massive number of devices. It is observed that in many cases the latency over large scale scenarios is still a limiting obstacle for relevant use cases. In addition to that, in such environments, even with a limited number of eMBB users being available, their experience is not satisfactory due to the received interference from new admitted users in scheduling time intervals. This interference is neither well considered nor managed in the above literature.

To the best of the authors knowledge, no literature has been found so far investigating the impact of highly loaded massive URLLC users in a mixed URLLC and eMBB traffic use cases that considers mitigating existing interference in the network. Therefore, efficient radio resource management (RRM) is required to minimize the latency of URLLC while enhancing the throughput of eMBB for such coexistence networking scenarios. This paper aims to contribute to fill up these research gaps.

B. CONTRIBUTION

With focus on these research gaps, in this paper we introduce an enhanced RRM scheme to minimize the latency of URLLC devices in a coexistence network scenario with eMBB for a cell-less RAN architecture. This RRM scheme will work in the following ways: firstly, it focuses on the latency enhancement where there is a large number of URLLC users and there is a need to provide service to the users in an efficient way to avoid the extra queuing delay caused by a lack of resources. Secondly, it enhances the resource management for eMBB users in a harmless manner, managing interference and avoiding performance degradation of the scheduled eMBB users in the same time interval. In this context, our proposed RRM scheme will enhance the network performance compared to existing works where there is high competition for resource allocation. The contribution of this paper can be summarized as:

- We propose an enhanced RRM scheme within a cell-less architecture that targets to ensure services to many users accessing the entire resources of the network. This scheme improves the latency performance by an efficient scheduling that considers the number of resources required for delivery of URLLC packets.
- We develop a time domain (TD) scheduler by proposing a ranking algorithm from a radio unit (RU) perspective which will support the efficiency of scheduling in terms of resource consumption in large-scale networks. This ranking algorithm is weighting the user associations criteria. Thanks to this, the probability of queuing delays for users due to lack of resources will be reduced in a particular scheduling interval. In addition to this, it will enhance the signal quality and throughput performance of URLLC users through improving the channel awareness factor in the scheduling metric.
- We introduce a frequency domain (FD) scheduling algorithm with the use of interference contribution ratio (ICR)-based approaches (as the other possible option in addition to throughput-based FD scheduler). It will avoid the eMBB users throughput degradation that can be caused by competition of newly admitted users to the network with existing ones. The proposed FD scheduler will consider the interference contribution of the resource blocks (RBs) while scheduling each pair of user and RB. Hence, in order to schedule eMBB users in the particular time interval, the impact on throughput performance will be considered in a cooperative manner. On the other hand, a throughput-based scheduler is the proposed option for scenarios where the number of scheduled eMBB users matter rather than the quality of their experience.

The organisation of the paper is as follows. The system model and URLLC latency components are described in Section II. In Section III the research problem is formulated mathematically and the RRM scheme is proposed. Section IV evaluates the performance and analyzes the results. Finally, the conclusion is made in Section V.

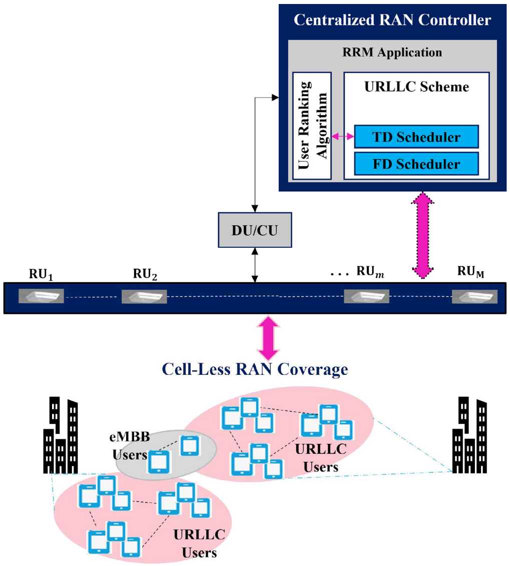

FIGURE 1. High level architectural view of a system model delivering URLLC service supporting large number of users in addition to few eMBB users.

II. SYSTEM MODEL AND URLLC LATENCY COMPONENTS

In this paper, we consider a downlink communication scenario with coexistence of eMBB and URLLC services. In the network, there are devices carrying URLLC services for traffic monitoring, emergency alarms, important security notices that need a precision service scheduling, etc. In addition, there are eMBB devices that could fully utilize the remaining resources. There is a central controller responsible for collecting information from users and radio resources. It also takes care of synchronization of the latest resource occupation updates for further scheduling and data transmission to each URLLC and eMBB devices considering the decided RRM.

A. SYSTEM MODEL

We assume a cell-less architecture of the RAN with an Urban Macro-URLLC environment as per ITU recommendation for URLLC scenarios [34]. In the following, let us consider a set of RUs $\mathcal{M} = \{1, \ldots, M\}$ and a set of URLLC users together with eMBB users $\mathcal{K} = \{1, \ldots, K\}$. M and K are the total number of RUs and UEs accordingly, where RUs are distributed in the network as depicted in Fig. 1 and a large number of URLLC users together with some eMBB devices are randomly distributed over the entire network area. The RUs and users are each equipped with single transmit/receive antennas. The channel gain between user $k \in \mathcal{K}$ and RU m is $h_{m,k}$ including pathloss and shadowing effects. P^m is the transmission power of RU m and σ^2 is the additive white Gaussian noise power at each receiver. For each URLLC user, small payloads of B bytes arrive at the network according to the traffic model known as FTP3 in 3GPP [35], corresponding to a Poisson point process with arrival rate of λ [payload/sec]. On the other hand, full buffer traffic with infinite payload is assumed for eMBB users. To reduce the transmission time for a tight target latency requirement, a mini-slot transmission time interval (TTI) of two orthogonal frequency division multiplexing (OFDM) symbols, corresponding to 0.143 msec is considered, where users can be multiplexed on a physical resource block (RB) resolution of 12 sub-carriers.

Each UE periodically measures the channel state information (CSI) for each resource element (RE) and reports a frequency-selective channel quality indicator (CQI) (it is specified in [36] for URLLC scenarios to guarantee low-probability of failure). It will allow dynamic link adaptation to select a proper Modulation and Coding Scheme (MCS) that assures a certain BLER target for the physical downlink shared channel (PDSCH) transmission. The well-known outer-loop link adaptation offset is applied to improve the MCS for achieving 0.1% BLER of the first data transmission and to analyze the impact of the proposed scheme in a high load scenario. The selection of the best MCS will ensure that we satisfy the target BLER given the Mutual Information Effective SINR Mapping (MIESM) [37]. In the case of no MCS satisfying the target BLER, the packet will not be scheduled until the channel quality is improved. The users report a negative acknowledgement (NACK) for failed packets and in that case the corresponding hybrid automatic repeat request (HARQ) retransmission is scheduled by the network. The HARQ algorithm is used based on [38]. The summary of notations used in this work is presented in Table 1.

B. LATENCY COMPONENTS

One-way URLLC latency ($\boldsymbol{L}$) contains the following components [32]

$$\boldsymbol{L} = d_{f_{a,q}} + d_{\text{tr}} + d_{\text{RUp}} + d_{\text{uep}} + d_{\text{HARQ}} \tag{1}$$

where $d_{f_{a,q}}$ and d_{tr} are the frame alignment and queuing delay and transmission time, respectively. Frame alignment is the random variable up to maximum one TTI, and queuing delay is the waiting time for the packet being in the RU buffer before being transmitted. It is considered that the packet is transmitted over one TTI. d_{RUp} and d_{uep} are the processing times at RU and UE, respectively. These processing times are assumed to be reduced to one TTI for each. In the case of a failure in packet transmission, the additional retransmission delay(s) is accounted for, where it is allowed up to four times retransmission. d_{HARQ} is the delay incurred by HARQ retransmissions. The minimum delay for each retransmission is equal to $d_{\text{HARQ}} = 4$ TTIs [27].

III. PROPOSED URLLC RADIO RESOURCE MANAGEMENT SCHEME

A. PROBLEM FORMULATION

In this work, we consider a network with a large number of URLLC users. Our target is to manage radio resource scheduling for URLLC users to experience their service with as small as possible communication latency subject to satisfying the proper reliability. In addition, the proposed scheme is applied to the network where also throughput

TABLE 1. Summary of notations.

Notation	Definition
$\mathcal{M}, \mathcal{K}, \mathcal{N}$	Set of RUs, users, and RBs, respectively.
$h_{m,k}$	Channel gain between user $k \in \mathcal{K}$ and RU $m \in \mathcal{M}$, including pathloss and shadowing effects.
P^m	Maximum transmission power of RU $m \in \mathcal{M}$.
σ^2	Additive white Gaussian noise power at each receiver.
λ	URLLC Packet arrival rate [payload/sec].
$\boldsymbol{L}$	One-way URLLC latency.
$d_{f_{a,q}}$	Frame alignment and queuing delay.
d_{tr}	Transmission time.
$d_{\text{RUp}}, d_{\text{uep}}$	Processing times at RU and UE, respectively.
d_{HARQ}	Delay incurred by HARQ retransmissions
$\boldsymbol{A}$	Matrix of size $K \times M$, represents the status of the users' connection to RUs.
$b_{k,m,n}$	Indicator to show allocation of RB n to k-th UE from a particular RU m $(A(k,m)=1)$.
$R_{k,m,n}$	Achievable throughput of RB n for user k, from a particular RU m.
$R^T_{k,m}$	Sum throughput of all RBs for user k, from a particular RU m.
$\Gamma_{k,m}$	Set of RBs allocated to k-th user from RU m where $b_{k,m,n}=1$.
k_{URLLC}	A particular URLLC user.
k_{eMBB}	A particular eMBB user.
N_i	The required number of RBs for a particular URLLC user associated with RU m.
N_T	$N_T \leq \lvert\mathcal{N}\rvert$, the total number of available RBs for each particular RU m.
$P_{r,\overline{n}}(k,m)$	RSRP of users averaged over bandwidth.
$\boldsymbol{Q}$	Matrix of size $K \times M$, represents the rankings of users from RUs perspective.
$\tau_{k,m}$	UE-RU association metric for URLLC users.
m^*	UE association metric for eMBB user to RU m^*.
$\hat{\Phi}_{k,n}$	Throughput-based UE-RB allocation metric.
$\Phi_{k,n}$	ICR-based UE-RB allocation metric.
$P_{r,\overline{k}}(m,n)$	average RSRP per RB from each RU m over associated users with that particular RU.
$I_{m,n}$	The interference received by the rest of the users in the network from allocating a RB n in particular RU m to its corresponding associated users.
$\lambda_{k,m,n}$	Interference contribution ration for allocating RB n to user k from RU m in the network.
B	Payload size.
λ	Packet arrival rate [payload/sec].

maximization is considered for the available eMBB users. That is obtained thanks to guaranteeing that the eMBB users receive minimum interference in occupied resources by URLLC users.

Let $\boldsymbol{A}$, which is a matrix of size $K \times M$, represents the status of the users' connection to RUs. If the user k is connected to RU m, we have $A(k,m) = 1$, otherwise $A(k,m) = 0$. $\mathcal{N} = \{1,\ldots,N\}$ is considered as the set of RBs, where the assigned RB n to k-th UE from a particular RU m $(A(k,m) = 1)$ is denoted by indicator $b_{k,m,n}$ and will be equal to $b_{k,m,n} = 1$ if being allocated, otherwise $b_{k,m,n} = 0$. $\Gamma_{k,m}$ is the set of RBs allocated to k-th user from RU m where $b_{k,m,n} = 1$ for each RB n and $L_{k,m}$ and $R_{k,m}$ are the corresponding latency and full-bandwidth throughput, respectively. The set of URLLC and eMBB users under a particular RU $m \in \mathcal{M}$ coverage is denoted by U_m.

The overall objective for URLLC users is to minimize the communication latency as

$$\underset{\boldsymbol{A},\boldsymbol{\Gamma_{k,m}}}{\arg\min}(L_{k,m}), \quad \forall k_{\text{URLLC}} \tag{2}$$

where k_{URLLC} is a particular URLLC user. At the same time, the objective for the eMBB users is as

$$\underset{\boldsymbol{A},\boldsymbol{\Gamma_{k,m}}}{\arg\max}(R_{k,m}), \quad \forall k_{\text{eMBB}} \tag{3}$$

where k_{eMBB} is a particular eMBB user.

Problems 2 and 3 are subject to:

$$\begin{aligned}
&C1: A(k,m) \in \{0,1\}, \quad \forall k = 1,\ldots,K, \quad \forall m = 1,\ldots,M\\
&C2: \sum_{k\in\mathcal{K}}\sum_{n\in\mathcal{N}} b_{k,m,n} \leq N_T, \quad \forall m = 1,\ldots,M\\
&C3: \sum_{n\in\mathcal{N}} b_{k_{\text{URLLC}},m,n} = N_i, \quad \forall k_{\text{URLLC}} \in U_m, \quad i = k_{\text{URLLC}},\\
&\qquad\qquad\qquad\qquad\qquad\qquad \forall m = 1,\ldots,M
\end{aligned}$$

where N_i, $N_i \leq N_T$ is the required number of RBs for a particular URLLC user associated with RU m, and N_T, $N_T \leq \lvert\mathcal{N}\rvert$ is the total number of available RBs for each particular RU m. The constraint C1 represents the binary value matrix $\boldsymbol{A}$. Constraint C2 is ensuring that the total number of allocated RBs per RU m does not exceed the total number of available RBs for each RU. According to constraint C3, each URLLC user will only be allocated the required number of RBs to receive URLLC packets. Problems (2) and (3) are non-linear integer complex problems which could be solved with exhaustive search with high complexity.

Assuming each user reports a CQI for S cells, the association will result in the complexity of $O((S+1)^{(K)})$. This is too high complexity for practical network implementations with a large number of URLLC users that need quick scheduling decisions in each TTI. Moreover, the complexity will be increased with RB allocation. Motivated by proposals from [32], this optimization will be performed through the solution of two sub-problems, namely, by a TD low complexity scheduler (optimized from the proposed TD scheduler in [32] to improve the latency performance of URLLC users) and a novel cooperative FD scheduler (to manage the interference when the number of users is large). URLLC payloads are scheduled initially in order to avoid extra latency. Therefore, eMBB users will be scheduled just after URLLC users. The applied scheme including TD and FD schedulers, which will be performed in sequence, is explained next. The high level view for the proposed RRM application is illustrated in Fig. 2.

B. USER ASSOCIATION

As we concentrate on low latency communication of high user-density scenarios with a large number of URLLC devices, the number of RBs is considered as a limiting factor which will cause extra delay for the users when they face a

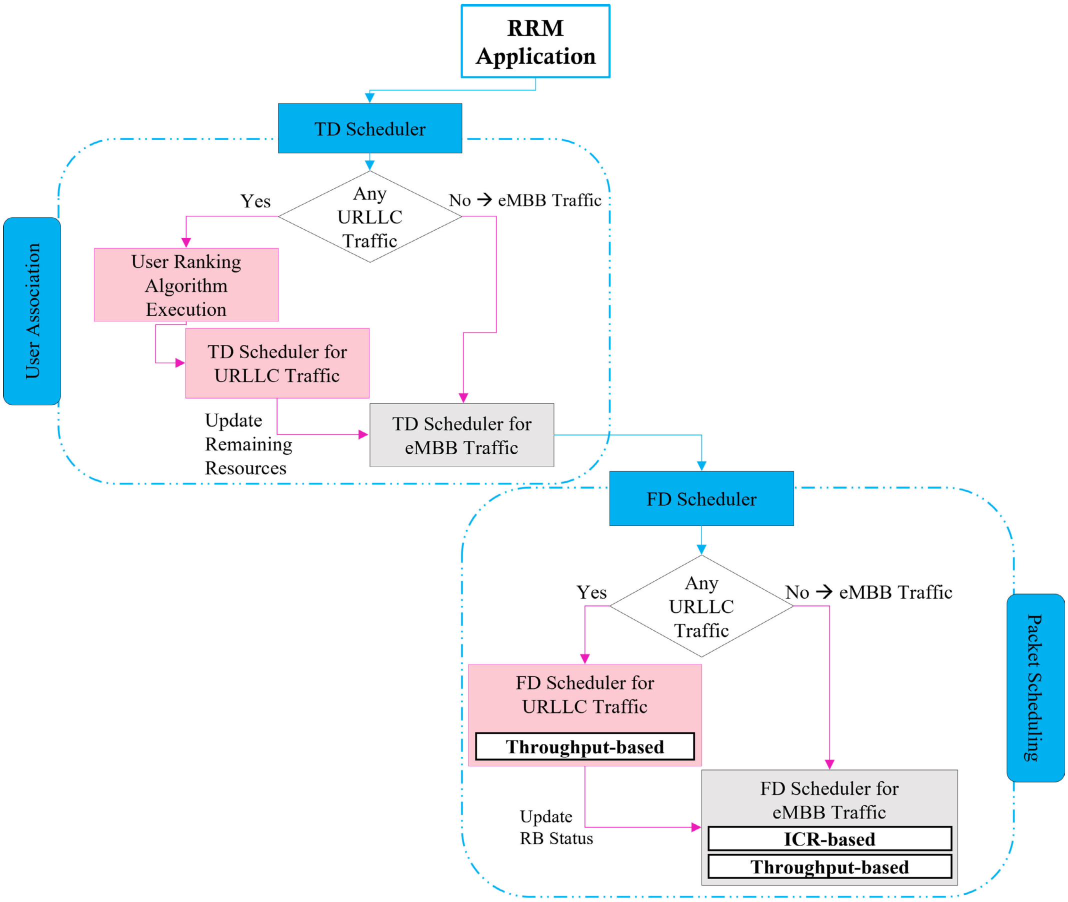

FIGURE 2. RRM Application high level view, including TD and FD schedulers.

lack of RBs. Therefore, the number of occupying resources (N_i) will be taken into consideration when the TD scheduler associates URLLC users with RUs for the set of RBs.

HARQ retransmissions are scheduled from a RU allocating RBs with highest CQI in priority. Afterwards, new payloads will be scheduled. It is assumed that packets will be scheduled without segmentation. As the utility function for URLLC users follows the problem (2) and for eMBB users it follows (3), thus we separate the TD schedulers for each corresponding traffic group, as follows.

```
Algorithm 1 User Ranking Algorithm
Input : $\boldsymbol{Q} = [0]_{K\times M}$; $\mathrm{Iq} = [0]_{K\times 1}$, $\mathcal{K}$; $\mathcal{M}$; $\boldsymbol{P_{r,\bar{n}}}$
Output: $\boldsymbol{Q}$
for $m = 1 : M$ do
    $\mathbf{Iq}^* = \mathrm{index}_k(\mathrm{sort}\ (P_{r,\bar{n}}(:, m)))$, sort in descending order
    $Q(:, m) = \mathrm{index}_k(\mathrm{sort}(\mathbf{Iq}^*))$, sort in ascending order
end for
return $\boldsymbol{Q}$
```

1) TD SCHEDULER FOR URLLC USERS

We note that the user association metric $\tau_{k,m}$ for pairs of users and RUs for the TD scheduler in [32] includes latency and normalized full-bandwidth throughput for each user k served by any RU m. Building on that, in order to mitigate the RB limitation problem for a large amount of URLLC users, we propose **Algorithm 1** for the ranking of users under each RU. Through this algorithm, rankings of users from RUs perspective regarding the RSRP of users averaged over bandwidth ($P_{r,\bar{n}}(k, m)$) will be stored in matrix $\boldsymbol{Q}$.

It supports optimization problem (2) while satisfying constraints C3 for URLLC users. The association metric $\tau_{k,m}$ normalized with a correction ranking factor $Q_{k,m}$, is defined as

$$\tau_{k,m} = L_{k,m} + \frac{R_{k,m}}{0.5\ln(Q_{k,m})\sum_{m\in\mathcal{M}} R_{k,m}}. \qquad (4)$$

The term $L_{k,m}$ is to prioritize users which are closer to the latency target. $R_{k,m}$ is for channel aware scheduling to decrease the HARQ probability. Moreover, the normalized ranking correction factor $0.5\ln(Q_{k,m})$ will avoid extra resources occupation and provide an opportunity for a higher number of users to be scheduled by RUs. Normalizing through $\sum_{m \in \mathcal{M}} R_{k,m}$ gives lower priority to the users which have the possibility of being associated with other RUs.

2) TD SCHEDULER FOR eMBB USERS

The user association metric m^* for eMBB users following (3) is targeting to maximize their throughput. Therefore, each eMBB user (k_{eMBB}) will be associated with the RU m^* which provides the highest wide-band CQI (i.e., highest RSRP $\boldsymbol{P_{r,\bar{n}}}$ for that particular eMBB user). It is worth to note that the eMBB users will be only scheduled if a particular RU m has remaining RBs after URLLC users allocation.

$$m^* = \underset{m \in \mathcal{M}}{\arg\max}\, (P_{r,\bar{n}}(k_{\text{eMBB}}, m)). \tag{5}$$

Considering the required number of RBs (N_i) per URLLC user and the available number of RBs per RU, the central RAN controller sequentially selects a pair (k, m) which has the highest metric $\tau_{k,m}$ and associates them if there are enough remaining RBs for the URLLC payload. All the remaining pairs corresponding to the selected users will be removed if the association is executed, otherwise, only that pair will be removed. The complexity of the proposed user association is $O(|\mathcal{M}|\,|\mathcal{K}|\log(|\mathcal{M}|\,|\mathcal{K}|))$ of the same order as [32]. After all the URLLC users being checked, the RAN controller will associate eMBB users with the RUs following the eMBB association metric, if there are still remaining RBs.

C. RESOURCE ALLOCATION

For URLLC traffic, a large number of URLLC users could cause a higher transmission delay for those UEs with lower SINR. For eMBB traffic, UEs will be scheduled with lower priority after URLLC traffic. Hence, a higher competition for RB allocation will worsen their performance. However, the design of an efficient resource allocation for such a large number of users will produce as a result that URLLC and eMBB UEs are being scheduled with the remaining RBs in a way that provides higher signal quality for them. Therefore, to support problems (2) and (3), we propose to use the following FD schedulers for URLLC and eMBB UEs, respectively. In the following, we propose an adaptation of previously existing schedulers in order to fulfil the requirements.

1) FD SCHEDULER FOR URLLC USERS

FD scheduler for URLLC traffic is subjected to provide data transmission with high reliability for all UEs, even those having low SINR.

- Throughput-based [32]: RB n will be allocated to URLLC user k which has the highest metric of

$$\hat{\Phi}_{k,n} = \underset{n \in \mathcal{N}}{\arg\max}\, \left(\frac{R_{k,m,n}}{R^T_{k,m}}\right) \tag{6}$$

where $R_{k,m,n}$ and $R^T_{k,m} = \sum_{n \in \mathcal{N}} R_{k,m,n}$, represent the achievable throughput of RB n and the sum throughput of all RBs for user k, respectively.

This allocation process will be continued until all URLLC users are allocated with their required number of RBs. Note that it was already verified in TD scheduler that each RU m has enough number of available RBs for its corresponding URLLC users.

2) FD SCHEDULER FOR eMBB USERS

eMBB users will be scheduled through the FD scheduler with all the remaining RBs per RU m after URLLC users. However, the received interference is impacting their throughput. FD scheduler allocates RBs to them targeting on maximizing their achieved throughput. This could be performed with competitive RB allocation (Throughput-based) or cooperative RB allocation (ICR-based).

- Throughput-based: In this option the same FD scheduler as for URLLC users could potentially be used (for RB allocation), which means using (6).
- ICR-based: Motivated by the Interference Contribution Ratio concept (ICR) [39], we propose ICR for RBs as the scheduling metric for eMBB users FD scheduler. Knowing sub-band CQI and channel measurements per RB at the central RAN controller, we define $P_{r,\bar{k}}(m, n)$ as average RSRP per RB from each RU m over associated users with that particular RU. Building on that, the interference received by the rest of the users in the network from allocating a RB n in particular RU m to its corresponding associated users is

$$I_{m,n} = \sum_{i \in \mathcal{M}, i \neq m} P_{r,\bar{k}}(i, n). \tag{7}$$

The FD scheduler allocates RB n to eMBB user k based on ICR metric for pairs of UEs and RBs that have the lowest metric of

$$\Phi_{k,n} = \underset{n \in \mathcal{N}}{\arg\min}\, (\lambda_{k,m,n}) \tag{8}$$

where $\lambda_{k,m,n}$ is defined as

$$\lambda_{k,m,n} = \frac{I_{m,n}}{A(k, m) P_r(k, m, n)}. \tag{9}$$

With the help of the proposed metric, eMBB UEs are allocated the RBs with the least interference contribution to the network.

The FD scheduler for eMBB users performs scheduling per RU m sequentially for pairs of users and RBs and will continue until no more RB remain in the corresponding RU. FD schedulers will remove the remaining pairs of allocated RB in each RU, in order to avoid reallocation of the same RB. As the result, eMBB users throughput will be optimized, which will be portrayed in the next section. Fig. 3 outlines the operation of the proposed RRM schemes for the URLLC and eMBB transmissions.

IV. PERFORMANCE EVALUATION AND RESULT ANALYSIS

A. SIMULATION SCENARIOS AND PARAMETERS

For the simulation setup, we assume a network topology with 500 m inter-site distance (ISD) and the total number

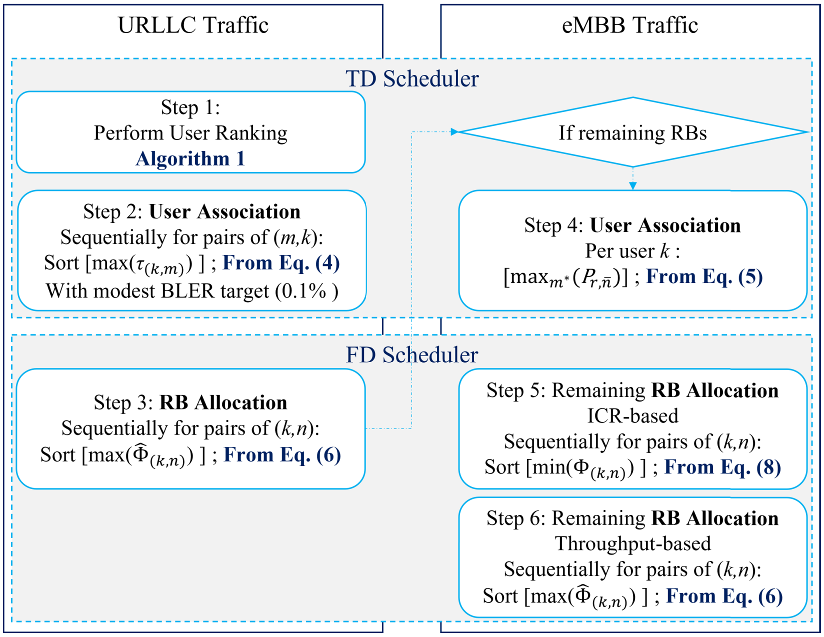

FIGURE 3. RRM Application - scheduling procedure for TD/FD schedulers.

TABLE 2. Simulation parameters.

Description	PARAMETER
Environment	3GPP Urban Macro (UMa); 6 RUs with 500 meters inter-site distance.
Propagation	Urban Macro-3D
Carrier	4 GHz, 20 MHz carrier bandwidth
PHY numerology	15 kHz sub-carrier spacing.
TTI sizes	0.143 msec corresponding to 2 OFDM symbols mini-slot.
MCS	QPSK to 64QAM, with the same encoding rates as specified for LTE.
Link adaptation	Dynamic MCS with outer-loop link adaptation with 0.1% initial BLER target
HARQ	Delay for each retransmission is equal to $d_{\text{HARQ}} = 4$ TTIs [27].
User distribution	1200-1500 URLLC users, 30 eMBB users.
Traffic model	eMBB: full buffer. URLLC: FTP3 downlink traffic with payload sizes of B = 200 bytes.
Delay d_{tr}, d_{RUp}, d_{uep}	1 TTI

of RUs is $M = 6$, with 20 MHz bandwidth over a carrier frequency of 4 GHz. RU height is 25 m and UE height is 1.5 m. The maximum transmit power for RU m is set as 44 dBm and the RU and UE antenna gains are assumed to be 8 dB and 0 dB respectively. Sub-carrier spacing is considered 15 kHz and TTI size is 0.143 msec corresponding to 2 OFDM symbols mini-slot. The UEs are randomly deployed over the entire network and the total number of URLLC and eMBB users are 1500 and 30, respectively. FTP3 downlink traffic with payload size of $B = 200$ bytes and arrival rate of 166.33 [payload/sec/UE] is set for URLLC users. Full buffer traffic has been considered for eMBB users. The channel model is implemented based on a simplified version from the defined model mapped with the Urban Macro test environment, and associated path-loss models used in simulations are from [34]. The KPI is one-way latency with 99.999% reliability. Other related configurations are aligned with the system-level simulation parameters in [34]. The summary of the simulation parameters is presented in Table 2.

B. SIMULATION RESULTS AND ANALYSIS

In this section, we evaluate the proposed scheduling scheme and compare it against our implementation of the reference scheme [32] with centralized scheduling as the baseline. These schemes are implemented for scheduling eMBB users in addition to a large number of URLLC users.

- Proposed scheme:
  TD scheduler uses metric (4) normalizing by user ranking for URLLC users and metric (5) maximizing achievable throughput for eMBB users.
  FD scheduler considers RB Throughput-based metric (6) for URLLC users. Either, RB Throughput-based metric (6) or ICR-based metric (8) are used for eMBB users.
- Reference scheme [32]:
  TD scheduler uses metric (4) without user ranking normalizing factor for URLLC users and metric (5) maximizing achievable throughput for eMBB users.
  FD scheduler considers the maximum throughput metric (6) for all users.

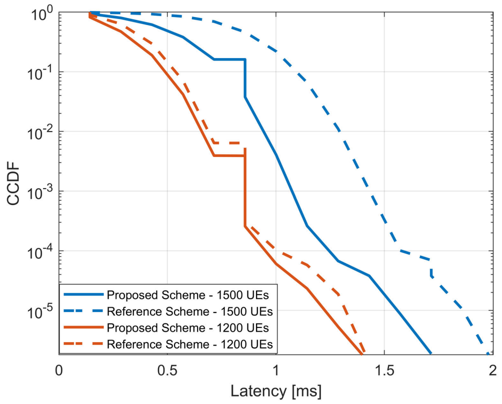

FIGURE 4. URLLC latency enhancement for different network scales with 1200 and 1500 URLLC Users.

The complementary cumulative distribution function (CCDF) of the latency is depicted in Fig. 4. With the assumed payload size of $B = 200$ and high offered load where the number of URLLC users is large, the latency performance is affected by users competing to access resources. Thus, access to the required number of RB for the users that have the URLLC buffer payload in the particular TTI might not be possible and force them to stay in the queue. As the offered load increases, this delay becomes more critical. It is observed in Fig. 4 that our proposed scheme provides significant gain in latency performance where there is a large number of URLLC users. At 10^{-5} outage, for the scenario where the number of users is 1200, our scheme has almost equivalent performance to the reference scheme with around 1.3 ms latency. In this scenario, HARQ occurs within $(10^{-1} - 10^{-3})$ percentile with the flat step in the simulation results. However, where the number of URLLC users is increased to 1500 UEs, there is a high competition to obtain the required number of RB by the users having packets in the buffer. The latency performance will be varying depending on the used scheduling policy. Our proposed scheme with 1.56 ms latency for the scenario with 1500 UEs outperforms the reference scheme which has 1.85 ms latency. This is equivalent to 29% latency reduction (closer to the target latency of 1 ms) for our proposed scheme. While, a HARQ has happened at below 10^{-1} percentile with the flat step. This gain in latency is because of saving RB by our proposed scheme due to adding the normalizing factor of user ranking. Therefore, our scheme is able to give the scheduling priority to the users which require a lower number of RBs from a particular RU. Thanks to this, in the scenario with a large number of URLLC users which is our focus in this work, our scheduler is able to perfectly manage users' competition.

Fig. 5 shows the impact of a high number of UEs on the transmission latency because of increasing the number of UEs that have to compete and wait for the available RB to receive their buffered data. This is the reflection of the importance of RB saving during the RB scheduling on latency for URLLC users.

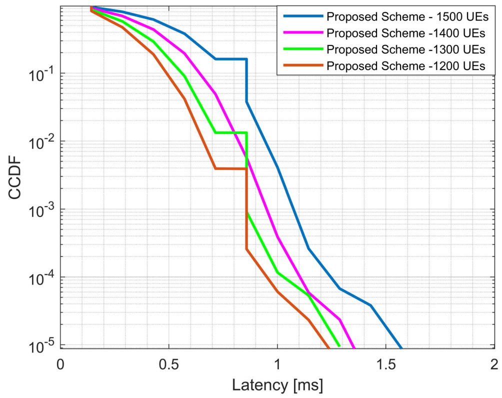

FIGURE 5. URLLC latency for different network scales with [1200 - 1500] URLLC Users.

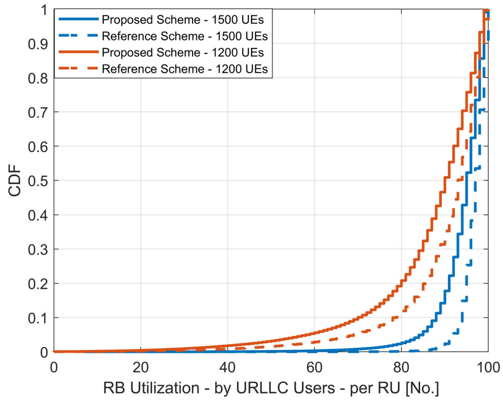

FIGURE 6. CDF of RB Utilization by URLLC Users per RU for different network scales with 1500 and 1200 URLLC Users.

Fig. 6 plots the cumulative distribution function (CDF) of RB utilization per RU by URLLC users. It shows the advantage of our scheme in saving more RBs during user association through the TD scheduler. The less RBs being allocated to each of the URLLC users, the less delay will be pushed to other URLLC users because of lack of required RBs. As it is depicted in Fig. 6, the gain of our TD scheduler in saving RBs against the reference scheme is the same for both of the scenarios with 1200 and 1500 UEs. However, as it was shown in Fig. 4, the result of this saving in latency performance is dominant when the number of UEs increased and competition over available RBs appeared.

Thanks to our proposed TD scheduler, which supports the network with enhanced RB utilization through the efficient user association, more RBs will remain for eMBB users. However, it is expected that throughput performance of URLLC users will also be enhanced because of the proposed UE-RU association technique which includes the channel awareness factor in TD scheduling metric (4).

Fig. 7 depicts CDF of the network throughput for URLLC users. We can see that our proposed scheme outperforms the reference scheduler. This is because of the user ranking factor which increases the strength of channel awareness in the UE-RU association.

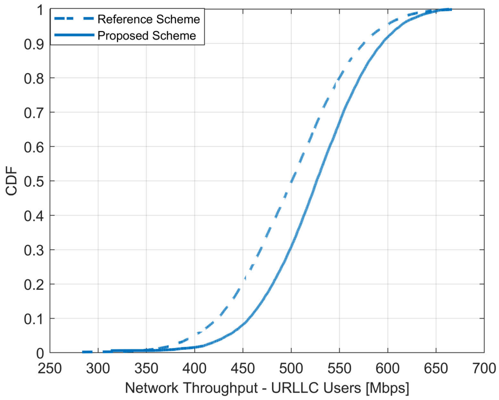

FIGURE 7. CDF of network throughput for 1500 URLLC Users.

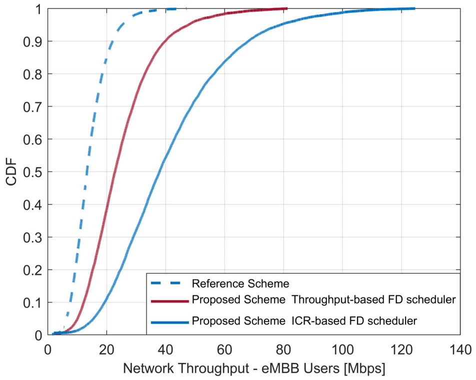

FIGURE 8. CDF of network throughput for scheduled eMBB Users.

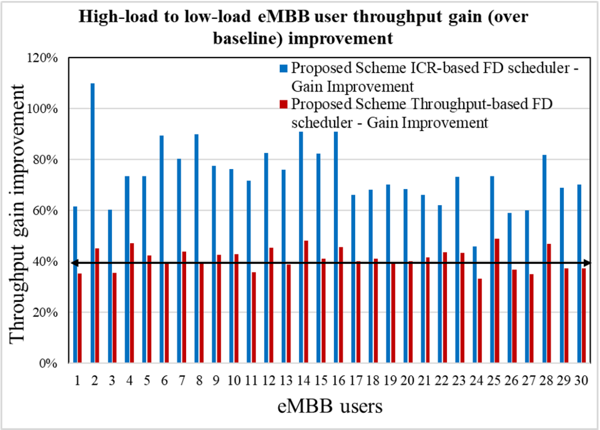

FIGURE 9. Average of eMBB user throughput gain (over baseline) improvement in a high-load scenario compared to a low-load scenario.

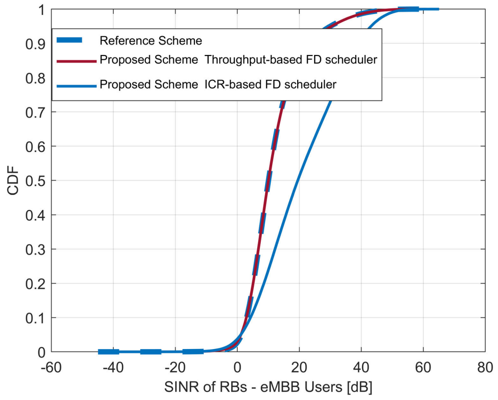

FIGURE 10. CDF of SINR of RBs for scheduled eMBB Users.

Fig. 8 shows the CDF of network throughput for eMBB users. It can be seen that our proposed scheme with ICR-based FD scheduler has higher gain in network throughput for eMBB users as compared to our proposed scheme with Throughput-based FD scheduler and our implementation of the reference scheme. The throughput enhancement happens because of two reasons. It is partly obtained by allocating a larger portion of bandwidth to the eMBB UEs because of saved RBs as the advantage of TD scheduler used for URLLC traffic. The improvement level due to this cause is shown in our proposed scheme with both ICR-based and Throughput-based scheduler. However, the extra throughput optimization is achieved through an optimized SINR level because of the efficient radio resource management (i.e., our proposed cooperative ICR-based FD scheduler).

The efficiency of our proposed scheme can be evaluated in comparison with other algorithms proposed to solve the similar problem, like [24], as well. In particular, the simulation results for eMBB throughput show the eMBB transmission will be impacted under a heavy URLLC traffic rate scenario. This is because of the priority of scheduling URLLC traffic over the ongoing eMBB transmission. However, their proposed scheme (which is a multi-agent DRL-based algorithm that can provide online decisions on resource allocation) performs the same irrespective of RB utilization. Hence, the network cannot provide a scalable performance when the number of URLLC/eMBB users (or their traffic load) increases. The results in [24] show that eMBB users will lose 30% of their average throughput in the case of not allocating the fixed resources for their service. This is while our proposed scheme provides 40% improvement for the average of eMBB users throughput gain over the baseline in the high-load scenario (assuming 1500 URLLC users) compared to the low-load scenario (assuming 1200 URLLC users). This is because of considering RB utilization during scheduling through the proposed user ranking algorithm. This result is shown in Fig. 9. The following simulation results prove the opportunity of scheduling more users provided as a result of saving RBs in addition to mitigating the interference in the network. It is worth noting that our simulation with respect to the higher URLLC traffic arrival rate is a worse scenario with larger payload size than that of [24].

The CDF of SINR of RBs for the scheduled eMBB UEs is presented in Fig. 10. The proposed scheme with ICR-based FD scheduler outperforms the proposed scheme with Through-based FD scheduler and the reference scheme. Our proposed efficient RB scheduling through ICR-based scheduler manages interference through allocation of RBs providing a stronger signal compared to their interference contribution in the SINR of UEs serving by other RUs. However, it is worth to note that SINR performance of

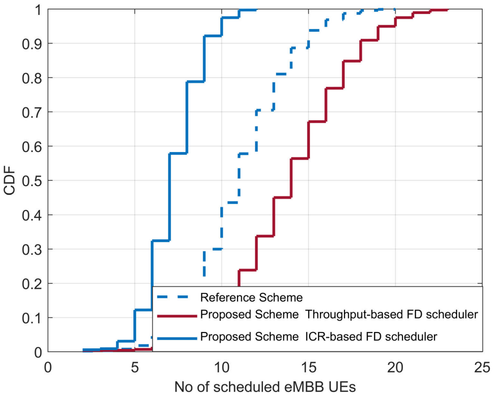

FIGURE 11. **CDF of number of scheduled eMBB Users.**

the proposed scheme with Throughput-based FD scheduler has almost the same performance as the reference scheme because of the competitive approach of RB allocation.

In contrary, the simulation result in Fig. 11 shows that the number of scheduled eMBB UEs (out of 30 dropped UEs in the network) is larger for the proposed scheme with the Throughput-based FD scheduler for eMBB traffic. This is because of the competitive allocation of this scheduler, which is not managing each UE's allocation impact when admitting it to the network. Whereas, cooperative ICR-based FD scheduler does admit eMBB UEs only if admitting them will not drop existing UEs' performance. Therefore, it is able to schedule a higher number of eMBB UEs at the cost of higher competition and larger network performance degradation. This proves the positive impact of the cooperative scheduler even for a small number of users in the cell-less RAN architecture. It is also shown that our proposed TD scheduler provides the possibility of scheduling more eMBB UEs because of less allocated RBs for URLLC traffic. Hence, depending on the expected KPI from the schedulers (i.e., based on the network throughput or number of scheduled eMBB UEs) the target FD scheduler could be activated for eMBB traffic.

As it is shown in Fig. 10, our proposed scheme has almost on average 90% SINR level improvement over allocated RBs to the scheduled eMBB users. This is a significant contribution for the networks with resource limitations for eMBB users as a result of cooperative scheduling. Moreover, Fig. 11 shows the opportunity for a number of eMBB UEs to be scheduled around 27% larger as compared to legacy schemes because of saving RBs from the scheduling phase of URLLC traffic. This gives operators the flexibility for decision making about the selection of FD scheduler in URLLC-eMBB traffic coexistence scenarios.

V. CONCLUSION

In this paper, an enhanced RRM scheme is proposed to handle a mixed URLLC and eMBB traffic for 5G and beyond cell-less RAN. The proposed scheme manages the RB utilization through an efficient user association to decrease the one-way latency for URLLC users. It also manages interference through a novel ICR-based resource allocation technique, which results in enhancing the throughput of eMBB users. Considering the latency for URLLC users and network throughput for eMBB users as the main objective functions, we make customized TD and FD schedulers within our proposed RRM scheme. Simulation results have shown that the proposed procedures provide a significant contribution for the scenarios with a large number of URLLC users in the network. Future research will consider the impact of transmission time and additional dynamic slicing algorithms for optimum coexistence of URLLC and eMBB users, enhancing the cell-less network performance as a strong enabling technology for beyond 5G networks.

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