Aalto University

Singh, Bikramjit; Tirkkonen, Olav; Li, Zexian; Uusitalo, Mikko

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Interference Coordination in Ultra-Reliable and Low Latency Communication Networks

Bikramjit Singh[†], Olav Tirkkonen[†], Zexian Li[§] and Mikko A. Uusitalo[§]

[†]*Department of Communications and Networking, Aalto University, Espoo, Finland*
{bikramjit.singh, olav.tirkkonen}@aalto.fi

[§]*Nokia Bell Labs, Espoo, Finland*
{zexian.li, mikko.uusitalo}@nokia-bell-labs.com

Abstract—5th Generation cellular communication is envisioned to enable connectivity for a wide range of new use cases. The focus on mission-critical communications, such as industrial automation and motion control, presses the demand for ultra-reliable communication. High availability, e.g., 99.999 % can be strived to reduce the outage probability. However, in multi-cell networks, interference from neighboring cells can be damaging in the ultra-reliable communication region. This requires a coordination amongst the interfering cells to relieve the interference in order to improve the network availability. In Multiple-Input, Multiple-Output based networks where the interference is colored, multiple base stations can coordinate by precluding the usage of precoders that increases the overall interference strongly. With this, multiple cells can jointly improve the minimum cell rate without inflicting harm to the other cell users, and thereby improve the network availability.

Keywords—5G; ultra-reliable and low latency communications (URLLC); availability; interference; max-min; MIMO

I. INTRODUCTION

The 5th Generation (5G) system is planned to be introduced in the early 2020s, enabling expansion of the current International Mobile Telecommunications (IMT) systems that go beyond Mobile Broadband (MBB) service, and envision to address new services and use cases. Ultra-Reliable and Low Latency Communication (URLLC) is one important enabler to support these new services. The most stringent requirement on URLLC currently being studied in 3GPP Radio Access Network working group is 99.999 % reliability under the radio latency bound of 1 ms [1]. For a small packet, the maximum packet error rate must not be higher than $1 - 0.99999 = 10^{-5}$, where maximum allowable radio latency, including potential retransmissions, is down to 1 ms. With the new numerology consideration for 5G new radio [2], e.g., shorter Transmission Time Interval (TTI) size of 0.125 ms with the help of mini-slot concept and each TTI contains both control and data information, there is a possibility to support transmissions with such reliability within 1 ms latency.

Packet transmission reliability suffers from transmission impairments such as path loss, shadowing, fading, interference, etc. State-of-the-art methods to ensure reliability utilizing various diversity schemes are very prevalent. Conventional methods to create temporal, spatial and frequency diversity work against the randomness in fast fading. Spatial diversity strategies are incapable against the shadowing. Increasing transmit power alone in order to accommodate big loss margins

due to strict requirements for URLLC [3] is not an option. Otherwise, this may cause increased interference problems in the adjacent regions, and the neighboring Base Stations (BSs) may react in the same manner to further degrade the URLLC services. To combat shadowing, routing diversity may be exploited by having multiple alternate communication routes to choose from. Multi-connectivity [4] is anothe alternative where a User Equipment (UE) has multiple connections on different carriers, possibly to different BSs. Different Radio Access Technologys (RATs) are used on the carriers, and they have different propagation characteristics. Multi-hop or flexible Device-to-Device selection mode also let the transceivers to choose the most appropriate routes [5], [6].

Interference control is another key component in delivering URLLC services. Interference arises with multiple UEs transmitting in the shared resource, e.g., within the same or neighboring cells. In [7], uplink UEs transmit in the same cell in a grant-free (contention-based) manner on a shared resource, and interferes with each other transmissions. The gains are undermined as no interference control mechanism is utilized, and the reliability is ensured just by repeating the packet transmissions. Unlike grant-free, grant-based access (uplink/downlink) can get rid of intra-cell interference by scheduling UEs on non-overlapping resources. Further, to boost rate availability in the network, max-min scheduler can be targeted. In case of multi-cell network, the implementation of max-min scheduling is fairly simple, e.g., in Single-Input, Single-Output (SISO) wireless communications system without power control, where UEs receive constant inter-cell interference from other cells. For example, in multi-cell network, SISO based BSs can adjust their power such that minimum rate in the network is improved. However, this simplicity vanishes in case of Multiple-Input, Multiple-Output (MIMO) networks due to changing (colored) inter-cell interference. If BSs implement max-min strategy independently, it may cause rate destruction of the UEs belonging to other cells.

To restrict colored interference, coordination between the BSs may be required. In [8], a dynamic switching mechanism is considered between coordinated and non-coordinated scheduling to adapt to a dynamically changing communication environment. The non-cooperation in [8] may be undesirable. A centralized scheduling scheme is utilized in [9] for interference avoidance in URLLC networks. However, centralized schemes are not adopted in practice, e.g., due to additional infrastructure requirement, critical information revelation. In [10], scheduling policy for coordinated beamforming is applied in heterogeneous

network. The macroBS's decision on precoder usage is taken if sum throughput of its own UE and UE served by the pico BS is higher with the precoder than without coordination. However, this does not guarantee rate improvement in URLLC region. A coordinated scheduling is proposed in [11] to reduce interference based on a UE selection. The precoder is determined considering the effects of downlink interference to UEs in the adjacent cells, and as a result, capacity improvement is limited. The proposal in [12] discusses inter-cell rank coordination between the interfering cells. In this, the affected BS sends the rank message to the interfering BSs, and based on the received feedback, updates are performed, e.g., re-scheduling the UEs, re-adjusting the transmission parameters, or re-adapting the transmission rank with respect to the feedback message.

In this work, we concentrate on downlink *URLLC availability* in a multi-user, multi-cell network. The latency component is taken into account by assuming shorter 5G new radio TTI size of 0.125 ms. To improve the resource efficiency, multiple cells use bandwidth with frequency reuse factor one. BSs administer URLLC services with an availability target of 99.999 %. This can be viewed as a requirement that the network is available for the targeted communication in 99.999 % of the locations (or the time) to the connected UEs of the deployed network. However, the frequency reuse necessitates inter-cell interference coordination to ensure the targeted availability. Neighboring BSs implement max-min strategy in such a way that the interference levels to the other cell's UEs are restrained. Hence, BSs coordinate to construct and exchange Background Interference Matrices (BIMs). The BIM contains the interference power that this BS inflicts to the opponent BS for the former's use of range of precoders. BSs thus work together to determine the MIMO precoder weights with a purpose to increase the minimum offered rate. Although, inter-cell interference coordination schemes including using BIMs have been discussed in great details for LTE systems. We however address the same issue for more critical 5G URLLC services, and while doing so, we believe that the novelty is introduced in related to the BIMs construction procedure and the related scheduling mechanism. For concrete simulation results, a factory environment with modeling parameters based on [13] is considered.

II. SYSTEM MODEL

We assume a network topology consisting of BSs and UEs in industrial environments such as factories, as shown in Fig. 1. We assume a deployment, where BSs are placed in the roof of a factory hall, and are in line-of-sight of each other. The UEs are static or semi-static, and typically not in line-of-sight.

We consider downlink communication, which works independently of uplink communication, e.g., Time Division Duplex (TDD) can be employed. Each UE uses all the bandwidth W available to the network and UEs are scheduled based on time-division multiplexing, i.e., each BS provides one downlink channel to one selected UE at a time. Time is considered to be slotted to sub-frames. Cell selection is based on Reference Signal Received Power. Each BS and UE is equipped with multiple antennas for MIMO wireless communications, i.e., multiple antennas are used for spatial multiplexing.

Considering MIMO channels with N_a antennas at each BS and UE, the achievable data rate on a link between BS i
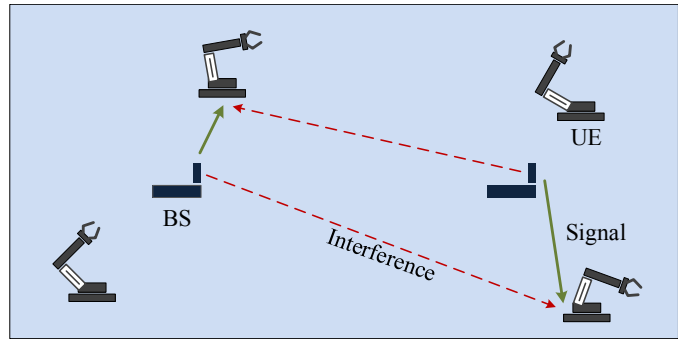

Fig. 1. URLLC in a factory scenario.

and UE j is given by*

$$r_{ij} = W \, t_{ij} \, \log_2 \det \left(\mathbb{1} + \mathbf{W}_{ij} \mathbf{H}_{ij} \mathbf{H}_{ij}^{\mathrm{H}} \mathbf{W}_{ij}^{\mathrm{H}} \mathbf{X}_j^{-1} p_i \right) \quad (1)$$

where W is the available bandwidth, $\mathbf{H}_{ij}$ is the channel matrix, $\mathbf{W}_{ij}$ is the precoding matrix, $\mathbb{1}$ is the N_a x N_a identity matrix, t_{ij} is the time scheduling weight of the data flow and p_i is the transmission power of BS i which constrained by a maximum transmission power allowed p^{max}, i.e., $p_i \leq p^{\mathrm{max}}$. Finally, the noise-plus-interference covariance matrix at UE j is

$$\mathbf{X}_j = \sigma_N^2 \mathbb{1} + \mathbf{I}_j$$

where σ_N^2 is the noise variance and $\mathbf{I}_j$ is the covariance matrix representing aggregate inter-cell interference.

The channel matrix $\mathbf{H}_{ij}$ and precoding matrix $\mathbf{W}_{ij}$ of a link have entries h_{ij}^{uv} and w_{ij}^{uv}; the channel coefficient and the applied precoding weight from antenna u of BS i to antenna v of UE j. The channel coefficient is $h_{ij}^{uv} = \sqrt{\Gamma_{ij}} \, \tilde{h}_{ij}^{uv}$ where $\tilde{h}_{ij}^{uv}$ represents the fast fading coefficient which is modeled as a zero-mean, unit variance circular complex Gaussian random variable. The link gain due to the large scale effects is modeled as $\Gamma_{ij} = \alpha \, d_{ij}^{-\eta} 10^{-\delta_{ij}/10}$ where $\alpha d_{ij}^{-\eta}$ represents the distance dependent path loss effects with d_{ij} the distance between BS and UE, $\alpha = 10^{\frac{-PL(d_o)}{10}} d_o^{\eta}$ is the path loss constant, η the path loss exponent and $PL(d_o)$ is the reference path loss at transmitter-receiver distance d_o. Shadow fading is represented by zero mean normally distributed random variables δ_{ij} with standard deviation σ_S.

III. INTERFERENCE COORDINATION

To ensure reliable communication, the proposed scheme coordinates the scheduling operation amongst neighboring BSs. BSs implement max-min fair scheduling, and while allocating the time resource to a UE, BSs ensure that they do not increase the interference level to neighboring cell's UEs. To coordinate scheduling, BSs may construct and exchange BIMs. A comprehensive description of BIMs can be found in [14]. BIM contains all possible interference values a UE can perceive from the other cell's precoded signals. With exchanged BIMs, BSs know the amount of interference power they can inflict while allocating TTIs to a UE. Hence only those TTIs are considered where BSs do not increase the interference from the current level to the other cell's UE. Each BS iteratively runs the scheduling algorithm and continue to do so until the minimum throughput stops incrementing, or the maximum latency is reached for URLLC. It is important to remark that the proposed scheme can be easily extended to 2-dimension resource block scheduling.

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*Notations: the transpose, complex conjugate, complex conjugate transpose (or Hermitian), trace and determinant operations for a matrix are denoted by $(\cdot)^{\mathrm{T}}$, $\overline{(\cdot)}$, $(\cdot)^{\mathrm{H}}$, $\mathrm{Tr}\{\cdot\}$ and $\det(\cdot)$ respectively.

Consider an example with two BSs A and B, where each administers services to two UEs, i.e., UE k and l, and UE p and q respectively. BSs employ TDD and use uplink/downlink sub-frame configuration 5 (corresponding to LTE as an example), and allocate downlink sub-frame to their UEs, see Fig. 2. Let us assume UE k's data rate is lesser than that of UE l. Therefore, BS A decides to allocate one additional sub-frame to UE k; either it will allocate a sub-frame 6 or 7 (UE k will receive same interference power on sub-frames 7-9 from the precoded signal meant for UE p by BS B, and therefore either of the three sub-frames can be chosen for UE k's allocation). The interference inflicted to UE k will be perceived differently on sub-frame 6 and 7, as the sub-frames are occupied by different UEs p and q respectively. Let us denote the interference powers from BS A due to its precoded signals for its UEs k and l to opponent cell's UEs p and q are $I_{A^k p}$, $I_{A^l p}$, and $I_{A^k q}$, $I_{A^l q}$ respectively. If BS A aims to allocate sub-frame 7 to UE k, then it compares the current interference power $I_{A^l q}$ with the projected interference power $I_{A^k p}$. If $I_{A^k p} \leq I_{A^l q}$, the desired sub-frame is allocated. With this, minimum rates (offered to the UEs) of the other cell B will never decrease, either it will remain the same, or increase in case the interference is decreased. In regard to implementation, the scheduling procedure scheme can be divided into two operational phases,

- Construction and exchange of the BIMs, and
- Iterative scheduling.

A. Construction and exchange of the BIMs

Before performing interference-aware max-min scheduling, BSs are required to exchange the BIMs. The operation requires a coordination amongst the BSs. With the BIM, we mean, a range of interference powers an BS can inflict on other cell's UEs. These interference powers constitute a countable finite set. This is because, each BS has some non-varying load, e.g., fixed number of operating machines, and therefore has the corresponding number of applied precoders. Hence BS can inflict the interference to the victim UE of the other cell, given its precoded signal set. To construct the BIM, first BS A will send a request to the other cell B for the BIM construction and its reporting. In the response, BS B will send an acknowledgment, and send a broadcast message to its UEs to request to report the interference powers perceived by them from BS A signal set. Once BS B fetches all these estimated interference power levels from its UEs, it then forwards the interference measurements to BS A. For instance, if BS A has a load of N UEs, then it possesses N corresponding precoders, i.e., $\{\mathbf{W}_{Aj}\}_{j=1,\ldots,N}$. Accordingly, BS A can inflict interference with powers of N different values to each UE belonging to other cell B. Assuming BS B having load of M UEs, we represent BIM for BS A as

$$\mathrm{BIM}_A = \begin{bmatrix} I_{A^1 1} & \cdots & I_{A^1 M} \\ \vdots & \ddots & \vdots \\ I_{A^N 1} & \cdots & I_{A^N M} \end{bmatrix}$$
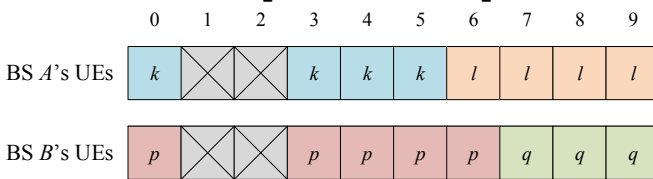

Fig. 2. Example with downlink sub-frames allocation.

where $I_{A^x y}$ is the interference power inflicted by BS A (using precoded signal meant for its UE x) to other cell B's UE y. The BS B's UEs $\{y : y = 1, \ldots, M\}$ measure the interference powers $I_{A^x y}$ and report back to BS B. Then BS B reports the findings, i.e., BIM_A to BS A. One important assumption is the synchronous operation among BSs, and there is fast X2 type of interface available. More flexible allocation design can allow the possibility of orthogonal use of time resources.

Furthermore, a flexible resource sharing can be applied. The reason is that at many time instants, the orthogonal sharing between the BSs may result in better availability for the outage UEs than in the case with shared resource use. For example, with shared use, the signal power S is approximately doubled due to doubling of resources, but there will be newly inflicted coordinated interference. It is a reasonable choice to use orthogonal sharing in the events where $\frac{S}{N} > \frac{2S}{N+I}$, i.e., average interference power I is more than the noise power N. This can be observed when BSs construct BIMs and estimate their signal-to-interference and noise ratio with or without shared transmission.

Now, certain questions arise that how practically feasible is the BIMs construction in regard to load variation, mobility, or even variation in channel conditions.

- Load variation - The given scenario targets URLLC service provisioning, e.g., for factory automation. The number of machines, e.g., robots, sensors, is usually fixed in the factory, and the increase or decrease in machines cannot be drastic. Thus, the load in the factory hall almost remains static for a period of time. Beside, various operators or BSs providing services in a factory hall may possess the complete identity of these machines.
- Mobility - In the given scenario, we consider robots or machines to be static or semi-static, i.e., with a small movement around its location, e.g., robotic arm motion. Hence, mobility is not high and BIMs exchange along with iterative scheduling can be implemented swiftly. However, this could also be checked in the extreme movement locations to test the effect of mobility. In case of more mobile robots or other elements, there could also be a set of BIMs for the couple of locations where these robots spend most of their time. So the BIMs would be location or robot state dependent. State refers to robot having a couple of operational states. There could be a BIM for each state.
- Channel conditions - Due to the relative stable environment, distance dependent path loss and shadowing will remain on quite a similar level, but the channel conditions between BS and UEs can be affected due to fast fading. As precoders are sensitive to fast fading, so at least, BIM would remain valid within the coherence time which can be long comparing to environments with high mobility. This also depends on how frequently BSs update their precoders, and if not, BIMs can continue to be valid for a longer time period.

Thus, in a factory automation scenario where load variation and mobility is not as prominent as channel conditions, the BIMs are not required to be updated at least within the fading coherence time. Therefore, the BIMs construction, and the BIMs exchange can be practically feasible.

B. Iterative scheduling

Once BSs exchange BIM_A and BIM_B, they perform scheduling operation iteratively. Consider BS A performs the max-min scheduling first. We list the optimization function as

$$\underset{[s]}{\text{maximize}} \quad \text{minimum}\,(R_A)$$

$$\text{subject to} \quad \sum_1^N t_{ij}\,(s) = 1,\ t_{ij} > 0,$$

$$I_{A^l y} \geq I_{A^k y},\ k := \arg\,\text{minimum}\,(R_A)$$

where R_A is the throughput set of BS A, i.e., $R_A = \{r_{Ax}\}$ with r_{Ax} is the achievable rate of UE's x belonging to BS A, and l denotes UE l of BS A to which TTI s is currently allocated. r_{ij} can be defined as $r_{Aj} = t_{ij}\rho_{ij}$ where t_{ij} is the time scheduling weight and ρ_{ij} is the spectral efficiency and from (1), it is defined as $\rho_{ij} = W\ \log_2 \det\left(\mathbb{1} + \mathbf{W}_{ij}\mathbf{H}_{ij}\mathbf{H}_{ij}^{\text{H}}\mathbf{W}_{ij}^{\text{H}}\mathbf{X}_j^{-1}p_i\right)$. According to the optimization, BS A allocates TTI s to its minimum rate UE k, but at the same time ensures that interference level does not increase to the other cell B's UE $y \in \{1, \ldots, M\}$ in the given TTI s. Here BS A checks BIM_A and allocates TTI s to UE q only if the precoded signal for UE k generates less interference than the precoded signal for UE l (currently serviced in the TTI s).

Once BS A has performed the scheduling, it will send the scheduling information to BS B containing which of its UE has been scheduled to which TTI in the frame. As of now, BS B is aware of the other cell's scheduling pattern, and hence applies the max-min scheduling and at the same time checks BIM_B so that it does not increase interference level to cell A's UEs. Both BSs continue to do so until minimum throughput cannot be increased further in both cells.

IV. NUMERICAL RESULTS

We consider a factory deployment scenario with two cells in a full sharing scenario. The parameters used for creating numerical results are summarized in Table I. For channel modeling, we apply the heavy clutter model of [13], which is characterized by moderate to heavy losses and is appropriate for transmissions between the BS in the roof and UE on the floor. The factory channel modeling parameters at 2.4 GHz

TABLE I.
NUMERICAL PARAMETERS

Factory hall dimension	50 m x 100 m x 5 m
Number of BSs/cells	2
Number of UEs	10
UE distribution	Uniform
Cell selection by UE	Reference Signal Received Power
Carrier frequency	2.4 GHz
Bandwidth (W)	10 MHz
Bandwidth efficiency	90%
Number of carriers	1
Power budget (p^{max})	24 dBm
Thermal noise power	-174 dBm/Hz
Noise figure	9 dB
Implementation margin	2 dB
Number of antennas (N_r)	2
Antenna Pattern	Omnidirectional, uncorrelated, single-polarized
MIMO configuration	2 x 2
MIMO gain	Multiplexing
Precoding type	Singular value decomposition with water-filling
Traffic model	Full-buffer

center frequency are listed in Table II. Path loss, shadowing and fading multi-antenna channels are properly modeled both for own-cell transmissions and inter-cell interference.

TABLE II.
FACTORY USE CASE PARAMETERS [13]

Factory topography	Path loss $PL(d_o)$ [dB] at $d_o = 15$ m	Path loss exponent (η)	Shadowing standard deviation (σ_S) [dB]
Line-of-sight	67.43	1.72	4.73
Heavy clutter	80.48	1.69	6.62

For each flow towards a UE, we identify the outage capacity subject to the availability target. A UE is considered in outage if a rate is not achievable with a given target reliability over a certain time window. For example, one may require the availability of data rate of at least 1 Mbps for 99.999 % of the time, and a UE is considered in outage if its data rate drops below 1 Mbps within the latency time window. Fig. 3 depicts the rate Cumulative Distribution Function (CDF) in the factory scenario without any coordination, and the zoom-in figure depicts the rates at availability target of 99.999 %, i.e., 0.3502 Mbps. If the link between BS and UE is in outage, the link is strongly attenuated and communication may be improved by carefully scheduling the UEs where it receives minimal interference in the resource blocks, and also coordinate with other BSs in reducing interference impact. We do not consider temporal diversity, e.g., in the form of retransmissions.

To assess the performance of interference coordination strategy for availability improvement at 99.999 % target, we compare the lower tail of the CDF of the resulting UE rate with or without coordination obtained over a finite time horizon of 1000 000 time units. For simplicity, in each instance, UE locations are uniformly distributed inside the factory hall. In the default case with no coordination, BSs independently allocate the time resources to the UEs in a round robin manner. The interference-aware scheduling (coordination) is selectively applied to the UEs which have default achievable rates situated in the worst 0.1 % distribution tail. We see in Fig. 4 that the
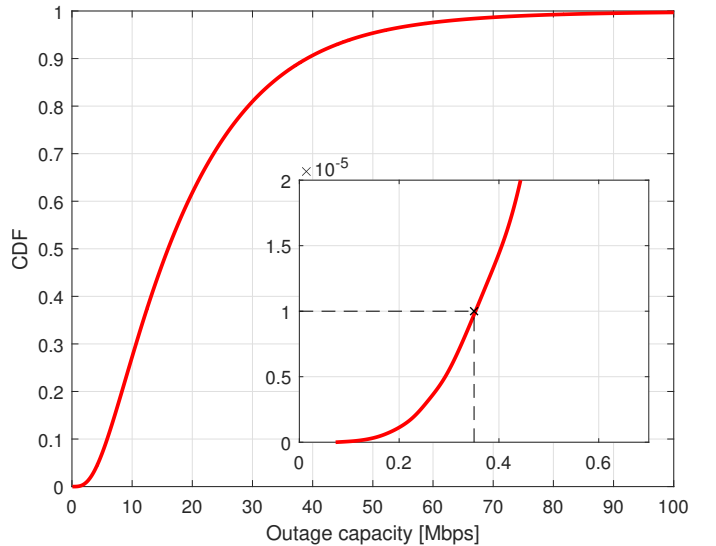

Fig. 3. UE rate CDF in the factory scenario. Zoom-in part depicts rate availability in the URLLC region around 99.999 % target.
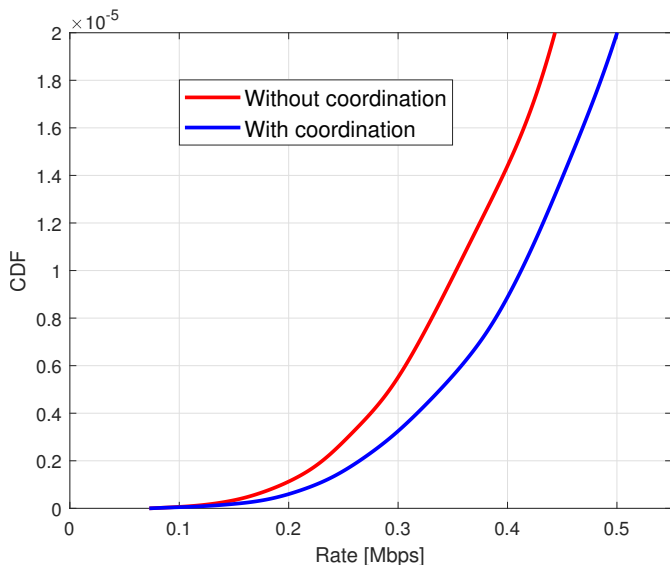
Fig. 4. Rate distribution for the outage UEs. Outage is defined as a rate below URLLC availability target of 99.999 %, as shown in Fig. 3. Default allocation without coordination vs. interference aware coordinated scheduling.

rate improvement at 99.999 % availability target is 14.7 %. Further in Fig. 5, we depict the outage UEs with and without coordination scheme. Outage is reduced by 43 %, which is considerable even though we witness smaller availability gains. Next we apply the coordination selectively to the UEs with the default rates in the worst 0.01 % distribution tail. Interestingly, the outage reduction remains the same, as depicted in Fig. 5. We see that with the applied scheme, the UEs in outage (or with poor achievable rates) are able to share resources with less interfering UEs. As a consequence, their rates are improved, and the outage probability is diminished.

V. CONCLUSION

Multi-cell networks sharing the same resource may inflict destructive interference and therefore necessitate interference coordination. The coordination becomes much more demanding if the focus is ultra-reliable and low latency communications. In these scenarios, base stations can employ channel state information based techniques, e.g., max-min scheduling to improve the guaranteed rate. In presence of colored interference that varies in time, neighboring base stations should coordinate so that the inflicted interference to others do not go beyond to the harmful levels. In a factory setting, e.g., with robots or cranes, the transmitting users' locations are static or semi-static, and therefore base stations can construct background interference matrices for all transmission possibilities from the interferes. Base stations can exchange these background interference matrices, and schedule their time resource in such a manner that minimum rate is maximized, and while doing so they ensure that the inflicted interference is at minimum to the neighboring users. In this manner, by appropriately choosing the transmission's time resource, base stations benefit from each other with reduced interference, and therefore improve the network availability in the ultra-reliable communication region.

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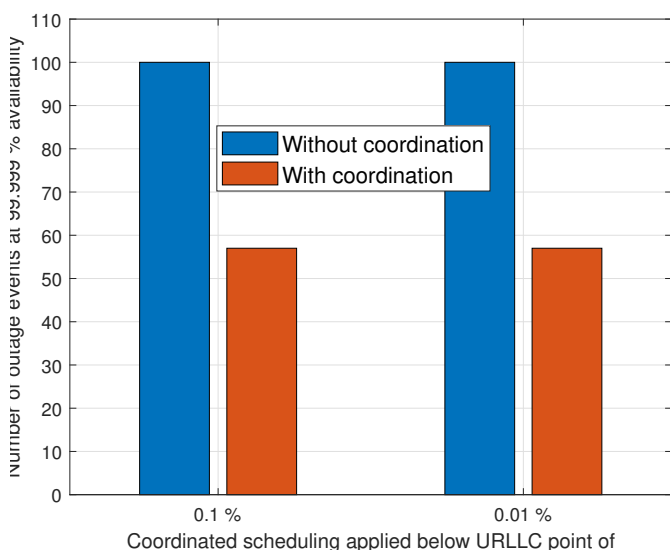
Fig. 5. Number of UEs in outage with and without coordinated scheduling. Outage is defined as a rate below URLLC availability target of 99.999 %, as shown in Fig. 3.