Interference Coordination for 5G New Radio

Beatriz Soret, Antonio De Domenico, Samer Bazzi, Nurul H. Mahmood, Klaus I. Pedersen

Abstract

The arrival of a 5G New Radio (NR) provides a unique opportunity for revisiting some of the Inter-Cell Interference Coordination (ICIC) mechanisms. The objective is twofold: to better exploit the benefits of ICIC in coherence with the rest of Radio Resource Management (RRM) principles in 5G, and to support new 5G classes of services and deployments. We propose several enhanced techniques. In the downlink, coordinated small cell discontinuous transmission aims at network interference control and energy consumption reduction, whereas inter-cell rank coordination can unleash the potential of advanced receivers with minimal control overhead. Besides, on-demand power boosting and coordinated muting can be tailored to meet Ultra-Reliable and Low Latency Communications (URLLC) requirements. In the uplink, inter-cell coordination of the pilot sequence configuration mitigates the inter-cell interference problem of such pilots, especially severe for cell-edge users. Results quantify the performance benefits of the different techniques under heterogeneous KPIs. We also discuss the standardization effort required for having each of these techniques included in the 5G NR specifications.

1. Overall Inter-Cell Interference Coordination design principles for the 5G New Radio

Co-channel inter-cell interference is known to be one of the limiting factors of cellular systems, and it has triggered numerous academic research studies and industrial standardization and implementation efforts in LTE/LTE-A [1]. Standardized network-based Inter-Cell Interference Coordination (ICIC) schemes for LTE range from basic coordination [2], to further enhanced ICIC [3], and towards more elaborate coordinated multi-point communication techniques [4]. The solutions for LTE were mainly designed to offer spectral efficiency benefits for data channel transmissions by applying various forms of inter-cell coordinated muting (or power adjustments), while offering only limited benefits for control channel performance.

5G NR is expected to experience a proliferation in the number of emerging use cases, categorized into three broad service groups [5]. Enhanced mobile broadband (eMBB), supporting an evolution of today's broadband traffic with a target peak data rate of 1 Gbps, will still be a key driver. Besides, 5G opens the door to new use cases with heterogeneous requirements, like ultra-reliable low-latency communications (URLLC), where messages must be correctly decoded with very high probability and in a very short time; and massive machine type communications (mMTC), catering
to a large number of (generally) low-data rate, low-cost services. The first two categories, eMBB and URLLC, will be the focus in the first phase of the standardization process.

In this paper, we present a set of recent interference management advances for 5G NR. To fulfill the promise of a comprehensive and integrated network, 5G must evolve from a network-oriented to a service-oriented paradigm, where differentiated services can coexist on the same infrastructure. Moreover, ICIC design principles must exploit the new degrees of freedom that have not been fully utilized in LTE, and need to be aligned with the envisioned more flexible radio resource management framework [6]. In this light, we describe solutions to address major interference challenges. In the downlink, we propose a scheme for joint interference control and energy efficiency in dense small cell scenarios [7] by means of enhanced methods for discontinuous transmissions at the cell level (cell DTX) based on fuzzy Q-learning [8]. Furthermore, we elaborate on the new opportunities that come from assuming multi-user multiple-input-multiple-output (MIMO) and advanced interference-aware receivers as the baseline for 5G [9]. Building on earlier work in [10] and [11], novel solutions for coordination of the maximum transmission rank between cells is presented. Another proposal is to support the challenging reliability and delay requirements of URLLC, which calls for highly agile and fast coordination techniques, offering benefits for both the control channel and data channel performance. Finally, we also pay attention to the uplink inter-cell pilot (also known as reference symbol) interference problem. In this context, inter-cell pilot sequence coordination techniques are proposed, translating into improved link performance as a result of enhanced channel estimation and coherent demodulation performance [12]. Another advantage of such techniques is their ability to support more users than current LTE solutions.

An overview of the four studied network-based ICIC mechanisms is shown in Table I. It is worth highlighting that the proposed schemes are complementary, addressing different interference challenges but sharing the 5G NR philosophy of a more dynamic coordination for a multi-service air interface. The details of the proposed mechanisms are presented in the next sections. In all cases, we strive for a generic design that is applicable both in distributed architectures as well as in scenarios with a centralized controller. Depending on whether the solution works in a fast or slow basis, the requirements to the backhaul (BH) in terms of signaling exchange between base station (BS) nodes are more or less critical, especially in the distributed architectures. For the sake of paper conciseness, each downlink (DL) solution is tailored for a given service (as emphasized in Table I), although the four proposals are applicable to both eMBB and URLLC.
Regarding the standardization effort to have the techniques supported in future 5G specifications, the requirements are categorized into inter-cell coordination among cells (through the so-called 5G Xn interface) and requirements to the UE in terms of e.g., measurements. For the former, such coordination includes exchange of information related to the traffic, load, rank, protected resources and sequence indices, and can happen in a slower or faster basis. For the UE requirements, we observe that the identification of the strongest interferer – the dominant interferer (DI) – is not possible in current LTE-A. For 5G NR, we identify a high potential from having new measurements to get such information reported from the UE. One possibility is to report the DI physical cell id together with a measure of the Dominant to Interference Ratio (DIR), defined as the ratio between the DI power to the rest of interference and noise power in the network. As it happens with the interference, the DIR can change very fast in fractional load scenarios [13], and therefore the LTE-A measures of received signal power are not sufficient.
Table I. Overview of proposed ICIC mechanisms

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Dir</th>
<th>Primary Services</th>
<th>Backhauling</th>
<th>Network coordination</th>
<th>UE requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-cell coordinated small cell DTX</td>
<td>DL</td>
<td>eMBB &amp; URLLC</td>
<td>Low latency</td>
<td>• In a distributed implementation, Xn shares the output of the DTX controller.</td>
<td>• As part of the CSI, the UE reports Dominant to Interference Ratio (DIR) to have information of the strongest aggressor.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>for fast</td>
<td>• At time t, the DTX controller at each small cell takes its decision based on the information received at t-1 by nearby small cells.</td>
<td>• This information can be updated on low frequency wrt the DTX coordination.</td>
</tr>
<tr>
<td>Inter-cell coordinated rank adaptation</td>
<td>DL</td>
<td>eMBB &amp; URLLC</td>
<td>Low latency</td>
<td>• In a distributed implementation, Xn negotiation of the rank limitation among the cell serving a victim UE and the aggressor cells.</td>
<td>• As part of the CSI, the UE reports Dominant to Interference Ratio (DIR) to have information of the strongest aggressor.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>for very fast</td>
<td>• The rank message indicates the maximum transmission rank for a given (set of) PRBs that the aggressor cell is recommended to use</td>
<td></td>
</tr>
<tr>
<td>On-demand power boost and cell muting</td>
<td>DL</td>
<td>eMBB &amp; URLLC</td>
<td>Low latency</td>
<td>The coordination in a distributed implementation is divided into two phases:</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>for very fast</td>
<td>• Xn negotiation of the protected PRBs works in a slower basis, and implies one cell serving a victim UE to negotiate with the list of relevant aggressors the set of PRBs that can be potentially protected</td>
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<tr>
<td></td>
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<td></td>
<td>• Xn activation of the muting works in a fast basis, and implies the cell sending the protected data to ask the aggressor cell to mute</td>
<td></td>
</tr>
<tr>
<td>Inter-cell coordination of uplink pilot RS sequences</td>
<td>UL</td>
<td>eMBB &amp; URLLC</td>
<td>No strict latency</td>
<td>Xn signaling of sequences indices in a centralized or distributed fashion</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>requirements</td>
<td>• In a centralized implementation, a central controller signals to a group of cells/base stations the sequence indices to be used in each cell of that group</td>
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<tr>
<td></td>
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<td></td>
<td>• In a distributed implementation, the concerned base stations exchange the sequence indices among each other</td>
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2. **Downlink inter-cell coordinated small cell DTX**

Cell Discontinuous Transmission (Cell DTX) is an energy saving technology that adapts the cell activity to its instantaneous load. Within each frame, the cell DTX will instantaneously activate (deactivate) the cell components and the associated functionalities when the user data is present (absent) in the cell queue. Furthermore, it is possible to increase the period in which a cell
switches off or mutes by maximizing the usage of the available frequency resources at each active TTI, i.e. trading off latency for energy efficiency.

In dense small cell deployments, this approach comes with the challenge of orchestrating the network activity in order to limit simultaneous activation of nearby cells. First, the optimal selection of the subset of small cells to activate at each frame is a combinatorial problem, which is complex to solve. Second, dormant cells cannot exchange information and implement baseline ICIC solutions or coordinated multipoint schemes. Finally, a reliable solution needs to take into account the stochastic nature of both the traffic and the radio channel.

Reinforcement learning solutions provide an efficient framework to learn optimal activation strategy by interacting with stochastic environments [8]. We design a fuzzy Q-learning based cell DTX controller which uses its decisions in the previous time slot to estimate the interference level experienced by the active small cells. In addition, the controller observes the queued data pending for transmission per cell, the expected capacity, and the requirements of the active services to decide whether to activate a small cell.

The sketch of the architecture and the detailed signaling exchange required by the scheme are shown in Figure 1 (a) and (b), respectively. Note that, the aggregation node buffers the data related to nearby small cells while the orchestration functions are deployed at the network controller. Additionally, the measurements related to the radio access network capacity can be forwarded to the controller node during the small cell activation. RRM and lower layer functions are implemented locally at the transmission points; thus, the controller and the small cells do not need to continuously exchange messages through the backhaul. On the contrary, a fully distributed architecture requires coordination across nearby small cells, which in turn increases the small cell (and the backhaul) energy consumption. In the same way, implementing centralized scheduling or coordinated beamforming schemes at the network controller 1) increases the network complexity, 2) needs the regular transmission of channel quality indicators over the backhaul link; and 3) is affected by the backhaul latency and capacity constraints. In any case, the proposed solution with reinforcement learning manages the small cell activity to limit the network energy consumption without reducing the system QoS.
3. Downlink inter-cell rank adaptation

In a MIMO scenario, the downlink serving rank (or number of streams) plays a major role in the interference reduction that advanced interference-aware receivers can attain. This is because significant interference suppression is only possible whenever at least one of the degrees of freedom at the receiver can be devoted to the detection of the interfering signal. In LTE, the rank selection per user is essentially performed in a selfish manner independently per link, without taking into account the interference caused by such selections. For 5G NR, the proposed inter-cell rank coordination mechanism can improve the network and the cell-edge user throughput by coordinating the generated inter-cell interference from the aggressor cell. Specifically, only the maximum rank of a cell is potentially limited, such that said cell can still freely decide the best rank for its served users within the imposed constraint. To further limit the complexity of the scheme, only the strongest interferer -- Dominant Interferer (DI) -- of the victim UEs is considered in the coordination, with UEs reporting the DIR together with the rest of channel state information.

Let us consider a multi-user MIMO time division duplexed (TDD) system. The available resources are divided into time-frequency slots, with the smallest unit being a physical resource block (PRB), corresponding to the duration of a single Time Transmission Interval (TTI) over a single frequency channel. The conventional approach in dealing with multi-user interference has been to either avoid interference altogether by orthogonalizing the communication links, or to maximize the desired throughput by treating the interference as noise. The former strategy leads to an
underutilization of the available resources, while the latter results in a reduced performance due to the excessive interference experienced at each receiver node.

The transmission towards a desired UE from its serving BS generates interference towards out-of-cell interfered receivers. A cell-edge user scheduled on a given set of PRBs in a neighboring cell is most likely to be affected by the transmission on the same PRBs, and hence requires interference coordination. Studies have shown that coordinating the transmission rank can help to improve the performance of interference suppressing receivers, such as the Interference Rejection Combining (IRC) [10].

The mechanism involves the following steps as illustrated in Figure 2:

1. The UEs report the DIR and CQI to the serving BS. The serving BS determines whether the DIR is above a certain pre-specified threshold, and rank coordination is only ‘invoked’ for those UEs with a strong DI. The UEs selected for rank coordination are then grouped according the DI, to avoid conflicting coordination requests from the same BS.

2. The serving BS decides what will be the maximum transmission rank for each of the UEs in each group, along with the interference rank it would like to have. The Signal to Interference and Noise (SINR) ratio is used for the decision. Particularly, the parameters \{target SINR, target outage, number of receive antennas\} are used as an input to the algorithm deciding own transmission rank and the desired interference rank. The ranks are chosen based on the estimated post IRC SINR\(^1\). The proposed rank coordination mechanism is not bound to any specific rank adaptation algorithm, though interference aware rank adaptation algorithms such as those presented in [10][11] are best suited for such applications.

3. The serving BS sends the desired rank message to the respective interfering BS. The desired rank message is indicated as the maximum allowable transmission rank for a given set of PRBs. These messages can be per single PRB, or several PRBs can be grouped into a single desired rank and priority level. The granularity provides a trade-off between performance vs. overhead and complexity.

4. The serving BS updates its transmission parameters according to the feedback message from the interfering BS. Such update can include re-scheduling the users, re-adjusting the

\(^1\)The post IRC SINR is the criterion for eMBB services. For URLLC, the probability of satisfying a target SINR can be used instead.
transmission parameters, or re-adapting the transmission rank with respect to the feedback message. The 5G TTI is expected to be shorter than the current 1 ms of LTE. The rank coordination could occur over a longer time basis (in the range of 5-10 ms), therefore suitable for heavy payload traffic spanning over multiple TTIs. For random intermittent traffic with small payload, the interference rank can be pre-coordinated to cater such bursty but critical payloads.

![Flowchart of Message Flow with multiple UEs](image)

Figure 2: Flowchart of Message Flow with multiple UEs

The algorithm in Figure 2 can be applied both in distributed and centralized architectures. Naturally, when having a centralized unit the scheme simplifies since there is no need for coordination messages among BSs. It is also worth to highlight that the proposed rank coordination can be applied both in wide area and small cell deployments.

4. **Downlink on-demand power boost and coordinated muting**

The SINR outage is a relevant metric for URLLC in 5G NR, and it can be improved with two well-known principles, namely power boost of the desired signal and muting or blanking of the interfering signal. These are two techniques already applied in 4G, whose application in 5G NR calls for a more dynamic setting able to accommodate different traffic requirements in a multi-service air interface. The other distinctive goal is to apply it not only to data channels but also to downlink control information carrying the scheduling grant, to further improve the gains. In this
direction, in-resource physical layer control signaling that follows the corresponding data transmission for each individual user signaling is a strong candidate for the future technology [6].

The proposed on-demand power boost and coordinated muting works as follows. On one hand, the power of a contiguous block of PRBs carrying both control scheduling information and corresponding data transmissions is boosted at the cell serving the victim UE. The power in the rest of the band should accordingly be de-boosted to keep a constant nominal power. Furthermore, the maximum value of allowed power boosting relative to the nominal value must be properly designed to limit the dynamic range and the Error Vector Magnitude (EVM) requirements. On the other hand, the same contiguous block of PRBs is muted in the aggressor cell, allowing the neighbouring cell to transmit both control channel scheduling information and data channel on those protected resources with enhanced signal and reduced interference. This principle is illustrated in Figure 3 (a).

One of the key points of the concept is being “on-demand”, i.e., activated only when needed. This implies deciding at each cell whether a UE has to be protected or not. The decision should take into account the potential performance benefit for the victim UE and the resource sacrifice for the muted cells. Similarly as in the rank-coordination, the complexity of this scheme is limited by coordinating only with the DI. The input for the decision includes information of the traffic requirements and the signal and interference conditions in the network. For the latter, each cell keeps a list of the DIs to the served critical users, sorted from the strongest to the weakest. The length of said list is N, which is known by all cells in the network and may depend on the traffic requirements or the system bandwidth, among others. In any case, N is not expected to be high when we account uniquely for the DIs. Moreover, the muting is applied only if the DI is close enough to the desired signal and considerably outstanding as compared to the rest of interferers and the system noise. Under these circumstances, the gain for the victim UE justifies the loss in available radio transmission resources for the rest of the network. The total amount of PRBs is then divided into N+1 PRB regions, such that it is always possible to negotiate an orthogonal set of PRBs among interfering cells (to avoid overlapping in the protected resources).

The power boost does not require any inter-cell coordination, since it works at the intra-cell level. As per the muting, cells need to agree on the set of muted resources and the activation. In a centralized architecture, a central entity keeps track of available information in terms of received signal and interference to the UEs in the network, and can rapidly take the network-wise muting decisions. For distributed architectures, the coordination is divided into two phases that work at
different time-scales. The idea is illustrated in Figure 3 (b). By default, all cells use all the PRBs. The negotiation phase takes place in a slower basis, with the goal of deciding the set of PRBs to be potentially (i.e. if needed) protected. With the agreement on the protected resources set-up, the cell serving the victim UE will ask the aggressor cell to mute during the transmission phase, happening every time a vulnerable packet arrives. This process is much faster since the specific PRBs have already been configured.

![Diagram](image)

**Figure 3: On-demand power boost and interference muting**

(a) Main principle (b) UE reporting and inter-cell coordination during the negotiation phase (slow basis) and the data transmission phase (fast basis)

### 5. Performance evaluation of downlink interference coordination

We briefly present and discuss the simulation evaluation of the three proposed downlink enhancements. The relative performance gains are shown in Figure 4. The KPIs are different for each case: user throughput for the small cell DTX and the inter-cell rank coordination, tailored for eMBB; and reliability for the on-demand power boost and cell muting, tailored for URLLC. The scenario comprises nineteen tri-sectorized macro cells in a hexagonal grid, with MxM MIMO and 10 MHz bandwidth. For the small cell DTX, there are also four small cells per sector.

The small cell DTX scenario has as baseline a DTX optimized only for energy saving and without interference management. There are thirty users requiring near-real time video traffic. We can see that the proposed solution outperforms the reference case both in 5%-ile and 50%-ile by more than 50%. The baseline cell DTX with data buffering, due to the uncoordinated small cell activation and transmission, results in high Packet Error Rate (PER), which, depending on the type of
service, may lead to mismatch the QoS constraints. This issue can be solved by the proposed scheme that results in a large improvement in terms of PER at the cost of a limited additional complexity and without affecting the energy consumption.

As per the inter-cell rank coordination, the technique is compared against baseline non-coordinated schemes. The traffic is full buffer. We use 8x8 MIMO, IRC receiver and a DIR threshold value of 5 dB. The KPI of interest is the UE throughput. It is shown that gains as high as 65% in the outage (5%-ile) and around 30% for the 50%-ile UE throughput are achieved with the rank coordination. Overall, the rank coordination scheme results in a more altruistic performance where significant outage throughput gains are obtained at the expense of minimal control overhead.

Finally, for the on-demand power boost and cell muting the shown KPI is the delay reduction for a $10^{-4}$ reliability target, and we evaluate the case with only power boost and with power boost and cell muting for a 2x2 MIMO. The traffic is a mix of UEs with sensitive information to be protected in the form of small packets of 32 bytes and first transmission BLER target of 1%, and background full buffer traffic to emulate eMBB with no special delay or reliability requirements. The delay of the protected data is reduced as much as 40% as compared to having no power boost, and up to 80% when also the inter-cell muting is activated. Although not shown, very high gains are also observed in the tail of the distribution, such that the maximum experienced delay is significantly reduced.
Figure 4: Relative performance gains of the three proposed DL ICIC mechanisms. For the small DTX and the rank coordination, the UE throughput in 5%-ile and median is plotted. The relative gain with power boost only and with combined power boost and cell muting is shown in terms of delay reduction for a $10^{-4}$ reliability, with a first transmission target BLER of 1%.

6. Uplink inter-cell pilot coordination

While previous sections focused on downlink coordination techniques, there are also challenges in the uplink. A well-known example is the uplink inter-cell pilot interference problem in systems with frequency reuse factor one. This problem arises when the assigned uplink pilot sequences across multiple cells --- which are non-orthogonal --- are scheduled on the same time-frequency resources. The received pilots from a target user suffer from pilot interference coming from neighboring cells, resulting in a bad channel estimation. This problem is especially severe for cell-edge users, as the power of interfering pilots is comparable to that of desired pilots. It leads to errors in uplink coherent demodulation, and is very detrimental in uplink multi-user MIMO scenarios which heavily rely on accurate channel knowledge to perform receive filtering. Additionally, in a calibrated time-division-duplex system where channel reciprocity holds, the BS can acquire the channel knowledge necessary for downlink multi-user MIMO precoding via uplink pilots sent by users. In this case, pilot interference leads to erroneous channel knowledge, which affects the precoding quality and resulting downlink throughput.
In LTE-A, users across cells are assigned non-orthogonal yet distinguishable sequences. These sequences are cyclic extended Zadoff-Chu (ZC) sequences, which are spread over the subcarriers of interest. Cyclic-extension is necessary to maximize the number of distinguishable sequences. The available sequences in each cell are constructed by phase rotating a root sequence identified by a root index, and are mutually orthogonal. The root sequences (and corresponding root indices) across cells are different. Different root sequences or phase rotations thereof are not orthogonal, though they are distinguishable via their root indices.

Few solutions exist on mitigating inter-cell pilot interference within the LTE-A OFDM context via a distributed or centralized sequence assignment over the cells. A related work is [14], where the authors propose an assignment of ZC sequences in an OFDM system, such that the channel estimation worst-case mean square error (MSE) is minimized. However, a key assumption of [14] is that user pilots occupy all available subcarriers, which is not the case in LTE-A, rendering the performed analysis inapplicable for the current technology. Furthermore, the base stations treat pilot interference as noise, which is suboptimal at high uplink signal-to-noise ratios (SNRs) occurring in, e.g., small-cell scenarios. In such scenarios, a better approach would be the suppression of pilot interference at the BS to recover the desired pilots with as little interference as possible.

LTE-A can allow for pilot orthogonality among multiple cells: a base station assigns, from its pool of available orthogonal sequences, pilot sequences for users in neighboring cells. Such a solution is not scalable for many 5G applications, as the number of users a BS can serve within its cell decreases.

One possibility to suppress the pilot interference and leave the number of served users within a cell unchanged can be realized by exchanging ZC root indices among BSs through the 5G Xn backhaul interface. An alternative implementation is a centralized approach with a central controller sending the indices of all concerned BSs to each BS. Both implementations allow a given BS to construct the sequences used in neighboring cells and perform channel estimation, including not only the channel of the desired user but also that of users in neighboring cells [12]. The channel of the former is then estimated with some residual interference (due to the non-orthogonality of sequences across the cells), while the estimated channels of the latter can be dropped or used according to the desired application (e.g., CoMP coordinated beamforming or joint transmission rely on the knowledge of channels of users in neighboring cells). The channel estimation is performed in the time domain and exploits the fact that in practical OFDM systems,
the number of taps is (much) smaller than the number of subcarriers, which results in reduced number of variables in the time domain (i.e. taps) that can be efficiently estimated. Going one step further, [12] proposes to optimize the choice of the used sequences such that the channel estimation MSE is further reduced. The gains of optimized sequence selection are mainly seen in the medium to high SNR regime where the non-orthogonality of used sequences becomes the limiting factor. Figure 5 shows the signaling steps necessary both for a centralized and a decentralized implementation. The first step consists of the signaling/exchange of sequence indices, while the second one involves informing the users within each cell of the chosen sequence within the respective cell. For the decentralized implementation, the order in which the steps are executed is not important.

Summing up, this procedure generalizes the idea of uplink CoMP data reception [4] to pilot sequence reception. It can be implemented for ZC as well as other types of sequences (e.g., pseudo-noise sequences). It improves the channel estimation quality for non-CoMP applications and allows efficient CoMP operation without reducing the number of users that can be simultaneously assigned sequences. As observed in [12], a careful choice of sequences can allow the achievable MSE to closely follow the interference-free MSE. In contrast to LTE solutions, keeping the number of users that can be served unchanged is especially important for eMBB and URLLC 5G services.

![Figure 5: Signaling steps in a centralized or decentralized implementation of pilot sequence allocation](image)
7. Conclusions

The arrival of new services and requirements for future 5G NR calls for a revision of inter-cell interference coordination mechanisms. In this paper, we identify and address some major interference challenges in the downlink and in the uplink. Although the four proposed schemes address different interference challenges, they are complementary and they all build in the 5G NR direction: being highly dynamic, flexible and multi-service capable. In the downlink, coordinated small cell discontinuous transmission aims at improving the network energy consumption while maintaining a high throughput performance, whereas on-demand power boosting and coordinated muting is tailored to meet URLLC requirements. Besides, inter-cell rank coordination can play a major role in scenarios with advanced interference-aware receivers. In the uplink, the pilot sequence interference is mitigated with proper coordination of the pilot sequences. The diversity in requirements of a multi-service network leads to a variety also in the KPIs, which is visible in the performance evaluation of the techniques. The performance gains show the clear benefits of network coordination with a limited complexity and standardization effort that has also been discussed. In all cases, we have strived for a generic design that is applicable both in distributed architectures as well as in scenarios with a centralized controller performing network-wise optimizations.

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