Interference Management Enablers for 5G Radio Access Networks

E. Pateromichelakis[1], H. Celik[2], R. Fantini[3], Ö. Bulakci[1], L. M. Campoy[4], D.M. Gutierrez-Estevez[6], A. M. Ibrahim[5] , F.J. Lorca[4], M. Shariat[6], M. Tesanovic[6], Y. Yang[5]

[1]Huawei Technologies ERC, Germany; [2]KTH, Sweden; [3]Telecom Italia, Italy; [4]Telefónica, Spain; [5]Intel Deutschland GmbH, Germany; [6]Samsung Electronics R&D Institute, UK

***Abstract*— Inter-cell interference can be seen as a huge challenge towards meeting the high capacity and coverage targets, as envisioned in 5G era. To this end, factors like the expected high density of access nodes reusing the same spectrum, the diverse sources of interference from heterogeneous access technologies, flexible wireless backhauling and the consideration of multiple 5G services with different KPIs can have strong impact on the way interference management is handled. This paper discusses three key interference management drivers, as good candidates for service-tailored optimization, which aim improving users' performance in terms of cell-edge throughput, provide energy-efficiency aware resource management and minimize the signalling overhead using BS clustering and context-awareness.**

Keywords—5G; Interference Management; Energy Efficiency

I. Introduction

The explosive growth in capacity and coverage demands emerged the evolution of traditional Radio Access Networks (RANs) towards highly densified and heterogeneous deployments as foreseen in some 5G scenarios. In 5G RANs, new challenges in terms of interference will arise mainly due to the employment of ultra-dense networks (UDNs). Furthermore, numerous other factors will strongly affect the way interference management is handled, e.g. the wide usage of beam-forming, the uplink/downlink (UL/DL) cross-interference in case of dynamic time-division duplex (TDD), novel modes of communication (e.g., self-backhauling, and cellular assisted D2D), and more diverse and stringent application requirements, e.g., latency-critical applications. It is, thus, required to develop an interference management functionality block that natively supports the new communication variants and effectively satisfies very different and demanding performance requirements.

Interference management in current cellular networks has been extensively studied in literature [1]. Various power control techniques have also been developed to provide enhanced performance within the network. In Long-Term Evolution-Advanced (LTE-Advanced) networks, such mechanisms were mainly studied and standardized from an UL perspective with a particular focus on keeping the receiver dynamic range below a pre-determined level [1] [2]. Nevertheless, in the case of ultra-dense deployments of access nodes in 5G networks, interference management schemes are gaining even more relevance and shall be tailored for the dynamic operation envisioned in such networks [3].

In addition, 5G RAN is expected to operate on various bands (below and above 6 GHz) and support various 5G services with wide range of requirements. Further, RAN moderation will imply dynamic radio topologies [4], e.g., activation/deactivation of nomadic access nodes (NNs) to attain on-demand network densification for coverage and capacity enhancement [5]. In such highly dense, heterogeneous and dynamic RAN deployments, the target agile interference management framework needs to cope with the momentarily changing interference conditions both on the UL and DL, and, hence, is a challenging task with multiple objectives and practical limitations regarding signalling and complexity. Therefore, a "toolbox" of interference management mechanisms will be required on demand to meet multiple objectives, which are prioritized differently per RAN deployment. For example, reducing signalling overhead / complexity will be key driver for high mobility scenarios and non-ideal backhaul. On the other hand, targeting high energy efficiency as main objective will be key driver for self-organized networks. Finally, having as main target the enhancement of cell edge throughput will be essential to boost performance at hotspot areas.

The remainder of this paper is as follows. Section II will introduce the agile resource management (RM) framework and the placement of Interference Management as key functionality block. In Section III, interference management mechanisms will be discussed by means of prioritizing edge-less experience in UDNs. In addition, Section IV will present energy efficiency-aware interference management technologies. Furthermore, in Section V we will show mechanisms that could reduce overhead to ensure that the use of sophisticated interference management will be efficient, in terms of signalling and complexity.

II. Interference management within Agile RM framework

A. Overview of technologies

In 5G RAN, one key RAN functionality framework, which is aimed to construct the agile RM framework [3], is the Interference Management functional block. The agile RM framework provides holistic RM solutions and air interface (AI) abstraction models that consider and exploit the novel aspects of 5G systems, such as, very diverse service requirements, existence of multiple AI variants (AIVs) in the overall AI, dynamic topologies, and novel communication modes.

In this context, some promising candidate Interference Management solutions are presented and categorized in three different classes, given the different objectives they prioritize to meet certain KPIs. That is,

- **Enhancing cell-edge throughput** by either using cooperative nomadic nodes in hotspot areas or by creating "interference-free" zones to enhance cell edge performance. This is further discussed in section III.A.
- **Enhancing energy efficiency** by dynamically switching on/off small cells, while providing coordinated multi-point transmission and reception (CoMP) mechanisms to deal with the potential user's performance degradation and the load increase at the surrounding cells. This is further elaborated in section III.B.
- **Reducing overhead** by clustering small cells and performing intra and inter-cluster CoMP mechanisms. This is described in more detail in section III.B.

Figure **1** illustrates an overview of the proposed interference management technologies, which are discussed in following sections, in a realistic Madrid grid, which can be seen as a toolbox of solutions that can adhere by the requirements of different use cases and deployments.

Figure 1 Interference management technologies for 5G

B. Measurements and Context Infomation

In addition, the measurement aspects are of key importance, since the context information required from multiple sources (e.g., user equipment, UE) needs to be identified for the above interference management solutions. Also, the challenges pertaining to 5G RAN deployments shall be rigorously captured and mechanisms reducing the overall overhead should be developed to cope with the expected high access node density and heterogeneity.

ITU-R WP5D, Revision 2 to Document 5D/TEMP/469-E, Chapter 5.3.8 defines context awareness as delivering context information in real-time on the network, devices, applications, the user and his environment to application and network layers in the context of IMT-2020. The context data are gathered by UE and BS, and then they are sent to specific databases in the network and exploited by extended and new radio management algorithms.

In heterogeneous 5G networks deploying dense and widespread small cells, there are many challenges, especially regarding the exploitation of user data for radio resource allocation. The amount of data to be gathered and the complexity of resource management algorithms need to be tracked carefully between the network performance enhancements they make available and the load they impose on both the BS and the UE in terms of data gathering, signaling, processing and storage. For example, since multiple use cases possibly with contradicting key performance indicators (KPIs) are identified in 5G, different air interface variants (AIVs) may be used in different use cases. To enable the switching from one AIV to another, the UE may need to perform separate measurements for each AIV.

Motivated by the above challenges, to ensure efficient interference management, the UE measurement context should be adopted to assist in reporting existing information with a more accurate estimation of parameters such as location, or even reporting new information such as the inter-AIV interference. Moreover, the exploitation of high frequencies will create the need for directional transmission schemes (e.g., via the beam-forming concept), which may imply updating the measurement context to support such new configurations (e.g., space tailored configurations). Furthermore, the UE could be able to maintain multiple measurement contexts, such as multiple configurations for multiple AIVs. In addition, the various 5G deployment scenarios, create the need of shaping proper UE measurement mechanisms related to other, equally important factors, (e.g., UE mobility state, time/frequency configurations).

The indicated functional extensions and changes on the UE measurement context are included in the following figure.

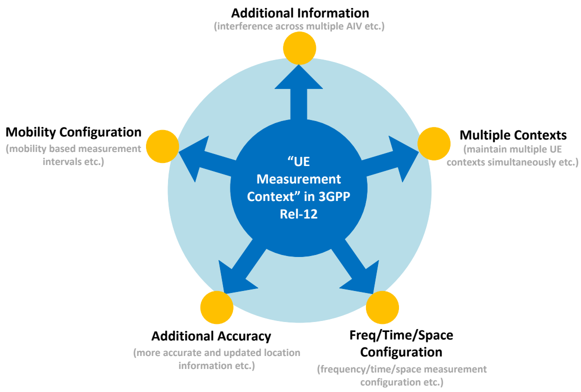

Figure 2 Possible changes on "UE Measurement Context"

III. Interference Management to Provide Edgeless Experience in UDNs

One of the key requirements for 5G is the enhancement of what is classically known as "cell-edge" performance, to ensure that every user is supported with consistent experience anywhere in the network. Co-channel interference is an inherent limitation of wireless systems employing universal frequency reuse. Overcoming interference is therefore essential in ensuring high capacity and wide coverage for end users, in addition to robust and efficient communication.

Different flavors of interference management are envisioned for 5G networks to improve cell-edge performance from centralized and adaptive downlink interference coordination in heterogeneous ultra-dense topologies to distributed cooperation strategies, in dynamic TDD operation, enabling CoMP schemes. Furthermore, inter-cell interference can be alleviated by altering the stochastic characteristics of interference to a non-Gaussian distribution, leading to creation of "interference free" zones. This is achieved when interfering cells switch to a new type of modulation scheme, improving cell-edge performance in victim cells. We explore such emerging schemes with more details in the next sub-sections.

A. UE-centric Interference Management in dynamic radio topologies

In ultra-dense heterogeneous RAN deployments, we aim at the improvement of the spectral efficiency by enhancing the spatial reuse. To this end, shared spectrum among different access technologies could be a potential solution in order to enable more efficient handling of resources. However, in such case, a holistic inter-cell RM framework is highly required to allocate RAN resources in a way that interference is mitigated while keeping the spectrum utilization high.

The concept of this work is to provide UE-centric interference management by means of selecting overlays of access nodes that can serve users individually, given their diverse service requirements. On top of that, coordinated resource allocation and joint transmission will be applied adaptively based on the backhaul conditions, the load constraints and the service type.

Here, we provide a case study for a hotspot area and a 5G RAN consisting of NNs under a macro-cell umbrella. In particular, we consider a dynamic network topology comprising non-static access nodes, which emerges as a promising notion enabling flexible network deployment and new services as highlighted in [4][6]. Within the framework of dynamic network topology, NNs can enable demand-driven service provisioning to increase the network capacity and/or to extend the cell coverage area NNs can be mounted on cars within a car-sharing fleet, taxi fleet or on privately owned cars. Further, NNs can be considered as a complementary enhancement to today's heterogeneous networks.

The key interference management mechanisms which are applied are Joint Transmission (JT) between the access links of NNs (i.e., between NNs and users) when it is possible. Only one mode of JT (coherent / closed-loop) is assumed in our case study, since we assumed static users and the backhaul to be ideal. The selection of candidate users for JT was is based on the difference of their channel measurements (RSRP) from serving and neighboring NNs. Given the number of users with low channel quality, a number of resource blocks (RBs) is reserved for JT and resource allocation between different NNs is performed. For the rest, coordinated scheduling is applied, where dynamic frequency partitioning (or muting of resources for some NNs) is performed. The dynamic frequency partitioning that is used in this study is based on [7] .

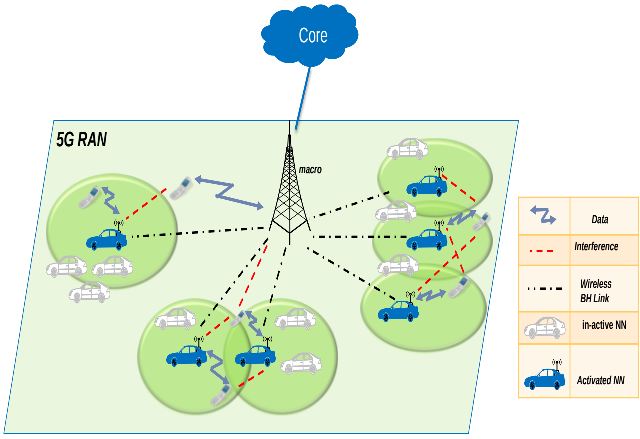

Figure 3 5G RAN exemplary model with nomadic nodes

Figure **3** shows an exemplary system model where a number of nomadic nodes are activated in hotspots to enhance capacity and coverage and also offload traffic from the macro. System level simulations were performed to evaluate the performance in such scenario with different number of activations of nomadic nodes in a hotspot area at the edges of the macro. For the simulation set-up, we used the Madrid grid deployment [8] and also used the channel parameters from 3GPP [9] (UMa for macro and UMi for NNs). Also, ideal backhaul is assumed for the NN-macro links.

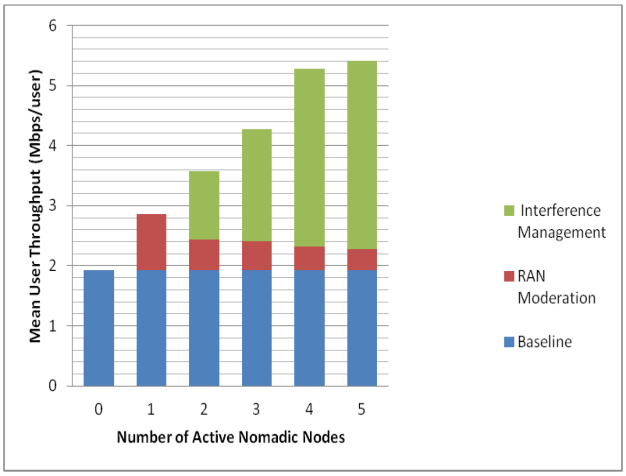

Figure 4 Mean user throughput for different NN activations

The results are demonstrated in Figure 4. The bars show the mean user throughput, in case we activate NNs and also if we perform Interference Management on top of that. The blue bar indicates the baseline, where all the users are attached to the macro. The red bar is the gain we see when we activate a number of NNs and offload some traffic from the macro. Finally, the green bar shows the gains when we also employ Coordination / Cooperation between the activated NNs. Interference management is crucial since as the number of NNs increases, the performance is degraded due to interference from surrounding NNs. So, Adaptive Interference Coordination and Cooperation (e.g., Coordinated Scheduling, Joint Transmission, Dynamic NN selection) mechanisms improve spectral efficiency in Dynamic Radio Topologies as well as the user throughput.

B. *Flexible Interference Management for 5G Air Interface variants*

It has been shown in the literature that the inter-cell interference (ICI) in conventional cellular networks employing orthogonal frequency division multiple-access (OFDMA) with Quadrature Amplitude Modulation (QAM) tends to approach a Gaussian distribution [18]. Furthermore, it has also been proved that the worst-case additive noise in wireless networks with respect to the channel capacity has a Gaussian distribution [19]. However, recent studies show that combining quadrature-amplitude modulation (QAM) with frequency-shift keying (FSK) into what is termed as frequency and quadrature-amplitude modulation (FQAM) [10] can be advantageous to change the pattern of ICI into non-Gaussian when applied at interfering cells, hence improving the performance of low SINR users in victim cells. In addition, FQAM can be applied along different dimensions of the radio resources, namely frequency, space and time, as follows: i) for a frequency-based split of resources, a flexible FQAM resource pool is negotiated among base stations; ii) for a spatial split of resources, certain interfering beams are selected for employment of FQAM, and iii) already established time-based procedures (e.g., ABS) are enhanced with FQAM-based subframes to effectively improve the data rate of the edge users experiencing heavy interference.

The main motivation behind this FQAM-based technique is to achieve more consistent performance and user quality of experience as the users move across the network from interference-free zones closer to certain BSs towards critical zones with contention from neighboring cells. To achieve this while maintaining high throughput in interfering cells, an agile resource management can be adopted where low-SINR users are scheduled from a flexible and adaptive reserved resource pool, negotiated between neighboring cells as depicted in Figure 4. The size and dynamism of this pool can be adjusted based on several factors e.g. the status of inter-BS interfaces as well as network configuration topology. If only light coordination within the cells is feasible, the size and location of the reserved pool can be commonly pre-determined and entered into look-up tables, minimizing the exchange of information between neighboring cells. This minimizes the signalling overhead which would otherwise be required if the information was updated regularly. If higher levels of coordination is possible, the size of reserved pool can be dynamically adjusted based on the level of load. In particular, each interfering cell may individually adjust the size of reserved pool based on the level of interference introduced to other cells. Therefore, the reserved pool (with FQAM) will not be necessarily uniform across interfering cells.

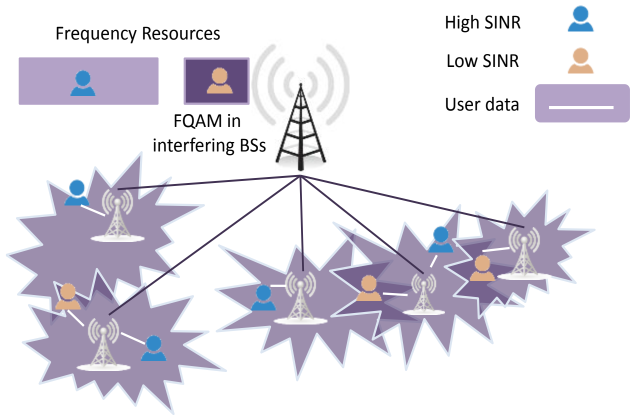

Figure 5 Concept illustration for flexible interference management

IV. Energy Efficiency-Aware interference management

While interference management has been traditionally investigated as a tool to increase spectral efficiency, in particular at cell-edge, recent studies showed that similar techniques can also be used to better exploit available resources, aiming to reduce the overall energy consumption when traffic in the network is below its peak.

A. *CoMP-assisted Dynamic Cell Switch-off*

In [7] it was proposed a mechanism to reduce the energy consumption in a non-fully loaded network, controlling a cluster of cells with a centralized scheduler that could switch off certain nodes, and at the same time exploit Joint Transmission (JT) and Dynamic Point Selection/Dynamic Point Blanking (DPS/DPB) on the remaining ones in order to address the traffic needs of the active users. The overall energy savings that could be achieved where analyzed considering power models proposed in the EARTH [11] project for macro and micro Base Stations (BS), considering equipment capabilities in 2010. However it is expected that future transmission nodes will be able to scale their consumption, based on the actual amount of traffic that it is served, in a more efficient way than nowadays system does.

The 5GREEN project [12] estimated that an improvement of 8% every year can be achieved in the dynamic part of power models, so that the overall power consumption will scale more significantly with the actual radiated power every year, and also “sleep” mechanism in the nodes will become more and more efficient (see Figure **6**).

Figure 6 shows the impact of power models suitable for 2020 transmission nodes considering the proposed scheme, comparing them to results that were reported in [7] with 2010 power models. Results shown in Figure 7 are obtained under the simplified Madrid Grid scenario described in [7].

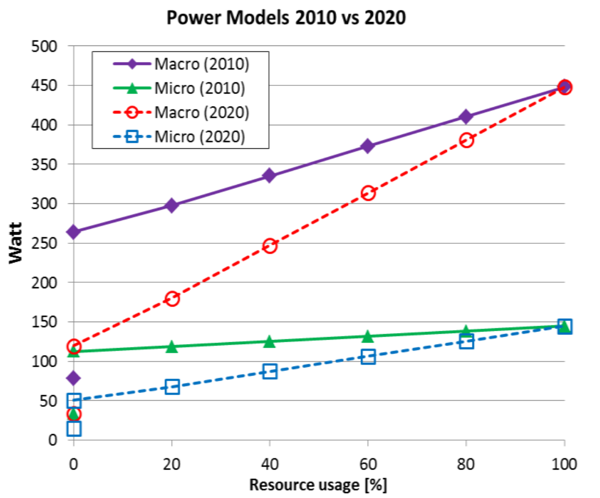

Figure 6 Power models for macro and micro BS in 2010 and 2020

It comprises 3 macro BS and 9 micro BS, each serving 10 users, and transmitting with a 10 MHz signal bandwidth. Different traffic loads have been considered, using Constant Bit Rate (CBR) traffic sources generating traffic at a given rate for each user, or the full buffer condition. Power consumption when no coordination between nodes (NoCoord) is exploited is compared with results obtained assuming the centralized scheduler that exploits JT and DPS/DPB for Energy Efficiency (EE JT).

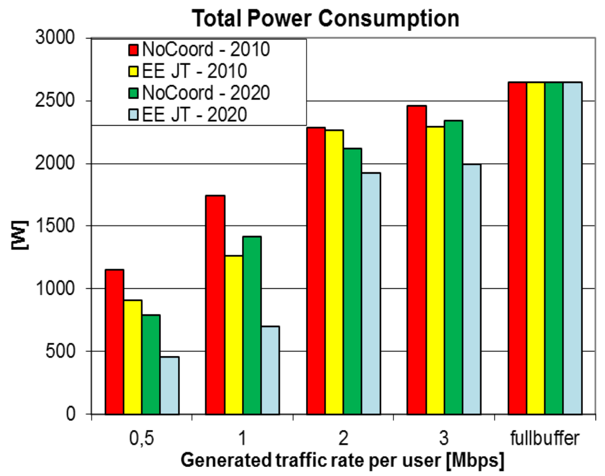

Figure 7 Comparison of power consumption with and without coordination with 2010 and 2020 power models

It appears that the higher dynamicity of future nodes can be even better exploited by the proposed scheme, which is able to deliver energy savings up to 51%, while only up to 27% savings were achieved with 2010 power models. More in general, the proposed approach showed that it is possible to trade off the additional capacity offered by interference management with reduced energy consumption, when traffic conditions allow doing so.

B. Multi-Cell Coordination for UDN Employing Dynamic TDD

To adapt to the fast traffic variations expected in dense 5G deployments, dynamic TDD [13] is considered an attractive solution that can provide significant performance gains. While it allows resource allocation to be performed on a much shorter time scale based on instantaneous traffic demands, it generates a challenging interference distribution with so-called same-entity (i.e., BS-to-BS and user-to-user) interferences caused by UL/DL traffic asymmetries, especially in the cell-edges. Despite this, dynamic TDD has shown promising results for indoor UDNs thanks to lower BS transmit powers due to closer BS-to-user proximity and a more favorable propagation environment with respect to co-channel interference.

In cases of low network utilization where some BSs may not have a user to serve, multi-cell coordination, e.g., joint transmission/joint reception (JT/JR) can be considered to improve the performance of nearby cells. This assumes a user-centric approach where a mobile is associated with multiple BSs at possibly different layers at the same time. Surprisingly, the combined problem of dynamic TDD and JT/JR remains largely unexplored in literature. The problem is complicated by the fact that complexity of the multi-cell coordination tends to grow quickly with network size [14]. For this reason, a distributed resource allocation that is scalable should be considered. Furthermore, determining which BSs to utilize and which to remain unused will depend on whether throughput (TP) or energy efficiency (EE) is considered, where the two will be in a trade-off relationship.

We illustrate this with a greedy search algorithm with the condition that an idle BS is only added if the system performance, either network throughput or network energy efficiency, is also improved. The proposed algorithm checks if the condition is satisfied for the worst users first and adds an idle BS as soon as it is. The procedure continues until all users have been checked or there are no more idle BSs to add.

In Figure 8, user throughputs for a system with varying traffic load is shown based on the BS deployment and environment of the virtual indoor office in [15] with blind dynamic TDD [16] used as a baseline. The term 'blind' refers to a system with no inter-cell coordination. The power gain from non-coherent JT/JR improves average system performance between 6-14% for moderate traffic load at 2 GHz operating frequency and 10 MHz transmission bandwidth, but at the expense of increased network power consumption as depicted in Figure 9. This is based on the power models in [17] for femtocells with 250 mW transmit power and sleep mode 4 in idle mode, compared to 100 mW transmit power for the mobiles. The trade-off is most visible in lower utilization regime, where adding more BSs is always preferred even if throughput gains are minuscule and relative power consumption increase is high.

In the case of a single user in the network and no interference (20% utilization), an already strong received signal (>30 dB) will be capped due to practical limitations detection capability. Adding more data streams will therefore not increase the system objective. At full traffic load (100% utilization), the gain is non-existent since there are no more idle BSs to add. So while this type of scheme may be beneficial in low and moderately loaded networks, at high network utilization its performance reduces to that of the baseline scheme.

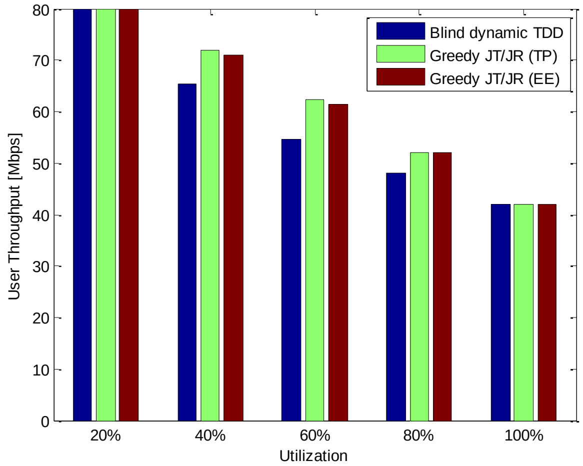

Figure 8 Average user throughput.

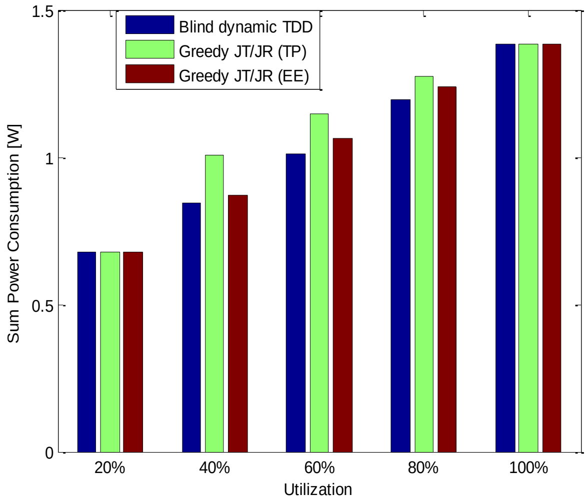

Figure 9 Network power consumption, including circuit power.

V. REDUCED-OVERHEAD INTERFERENCE MITIGATION

Some scenarios with reduced backhaul performance are also foreseen in 5G, as fast small cells deployments in low coverage areas. In these scenarios, one key topic for offering an interference controlled environment to the UEs is the optimization of overhead associated to the interference management mechanism.

Therefore, the design of interference management mechanisms, able to be deployed with low throughput and high delay backhaul (even below current values in X2 interface) will enable 5G deployment in such scenarios.

The approach researched is based on the implementation of specifics precoding (spreading and scrambling) to the transmitted complex baseband symbols. This spreading precoding is carried out over a number of consecutive time transmission intervals (TTIs).

Implementing this interference mitigation procedure for coordination of different access points requires only the interchange of information of the orthogonal coordination patterns to be used by each cell in the cluster. In Figure **10**, the functional blocks required for implementing the proposed interference mitigation are shown. In addition, the UE should be aware of the orthogonal pattern of the cell to which it is connected. Since this is a low overhead, it could be included easily in the Down Link Control Channel.

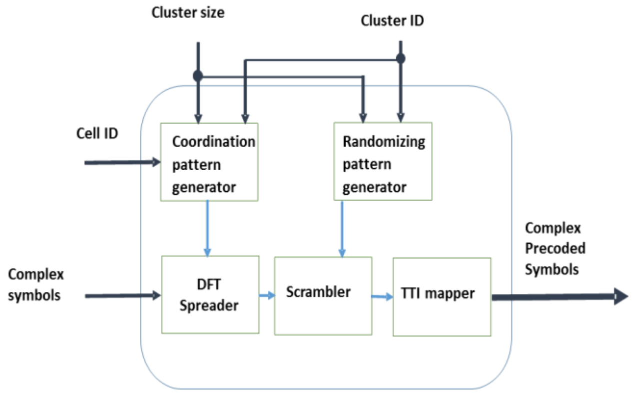

Figure 10 Transmission Reception Point functional blocks implementing reduced overhead interference mitigation

Once the pattern is known, the UEs implement descrambling and de-spreading procedures to cancel the interference generated by access points in the same coordination cluster, since the precoding introduces orthogonality between them.

It is worthy to note that, this interference migration procedure does not only provide orthogonality between signals from different access points in the cluster, but also provides some degree of protection against the interference from access points out of the coordination cluster, enhancing the SINR ratio in a similar way than usual spread-spectrum techniques interfered by uncoordinated signal in the same time frequency grid. The drawback of this technique will be de increase of latency, since several TTIs will be needed to transmit any packet to the UEs selected for this interference avoidance mechanism. However not all UEs in the area need to implement it, but only those which already bad service due to inter cell interferences.

CONCLUSION

In this paper, an Agile Interference Management framework was presented focusing on heterogeneous UDNs, which is a key scenario in 5G RAN. In this context, some key drivers which necessitate the evolution of interference management in 5G were further elaborated. To this end, providing edge-less experience to the users by either employing dynamic radio topologies (using cooperative NNs) or by providing “interference free” zones was analyzed and evaluated. Also, energy-efficient aware interference management mechanisms using CoMP and dynamic TDD principles were also discussed and evaluated as candidate solutions. Finally, since the signalling overhead might become a burden towards achieving high performance gains, we discussed potential solutions to address the tradeoff between signalling overhead and interference management.

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