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Resource and Mobility Management in the Network Layer of 5G Cellular Ultra-Dense Networks

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Abstract: The provision of very high capacity is one of the big challenges of the 5G cellular technology. This challenge will not be met using traditional approaches like increasing spectral efficiency and bandwidth, as witnessed in previous technology generations. Cell densification will play a major role thanks to its ability to increase the spatial reuse of the available resources. However, this solution is accompanied by some additional management challenges. In this article, we analyze and present the most promising solutions identified in the METIS project for the most relevant network layer challenges of cell densification: resource, interference and mobility management.

I. Introduction

Network densification manifesting in deployments of small cells (SCs) is an ongoing trend in contemporary cellular networks. Although SCs were already commercially available for the 2G and 3G technologies, the LTE and LTE-A standards provide technical solutions that exploit the local nature of such deployments. SCs are well suited for handling large traffic demands in hotspot areas with noticeable proliferation over the last years of high-end devices capable of processing data heavy content, e.g. high definition video. Moreover, people expect to have a broadband experience not only at home or office, but also outdoors. These two trends combined create a massive upsurge of cellular traffic, often referred to as the x1000 traffic volume

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challenge [1]. The next generation of cellular technology –5G– is expected to provide an economically justified system that will cater for this massive demand and extravagant user requirements.

The performance of modern cellular networks, mainly limited by the radio access network, is usually enhanced through solutions aiming at improving spectral efficiency, such as advanced antenna techniques (including the use of massive number of antennas) and endeavors of cellular industry to obtain more spectrum for wireless transmission in low and high frequency bands [1]. Despite technical challenges, this way forward is definitely a promising direction to improve capacity of future 5G networks, but, without a doubt, they will not be sufficient to provide a ubiquitous high-end user experience for the 2020-and-beyond mobile society. As proven in contemporary cellular networks, in order to satisfy growing user demands, improved spectral efficiency should be accompanied by further cell densification, especially in dense urban areas and indoors. Massive roll-out of SCs immediately poses a question on its economic feasibility. SC solutions available today rely on methods such as distributed antenna systems, unlicensed spectrum, or user-deployed SCs in order to bring down the deployment costs. SCs can be also extended to moving relays or nomadic cells where antenna systems exploiting wireless backhaul are mounted on cars, buses or trains, in order to provide a broadband experience to users inside or in proximity of vehicles.

The above-mentioned factors suggest that further deployment densification, resulting in ultra-dense network (UDN), is inevitable, which has interesting consequences for future networks operations. Shrunken cell sizes lead to reduced number of users served simultaneously by individual SCs over a geographical area, and hence to sharing the radio resources among fewer users. Moreover, smaller user-to-access-node distances decrease the probability of severe shadowing. This factor plays a major role in wave propagation at higher frequencies, which are interesting due to the availability of large bandwidths. Higher frequencies are a perfect fit for UDNs since, paradoxically, their higher attenuation limits the interference to neighboring sites and users. On the other hand, fewer users per cell leads to a more bursty activity profile of SCs. In combination with the time division duplexing (TDD) mode, which is expected to be extensively used in 5G due to its capability to adapt to dynamic traffic demands, this will pose a significant challenge to future 5G resource allocation schemes. It is still an open question to which extent advanced receivers and transmission schemes will be able to cope with the dynamic interferences [2]. Another challenge expected in UDNs is the heterogeneity of the 5G deployment. 5G is expected not only to introduce new access technologies, but also to reuse legacy 3GPP systems as well as IEEE technologies in order to provide the required user experience exactly where it is needed. This complicated deployment is very demanding from the mobility point of view, but it is also an opportunity for future devices to use specific technologies or layers in order to provide the necessary performance. How to efficiently detect and exploit this heterogeneous environment is definitely one of the most important challenges for the UDN design.

All aforementioned factors pose a question mark on the resource, interference and mobility management schemes that are used in current cellular networks, and they call for new methods, which will be able to fully exploit the benefits of SC deployments. This article provides an overview of some of the most promising network layer techniques identified in the METIS project [3]. First, we present two types of techniques related with the resource and interference management. In the methods of the first type, which directly coordinate interference in the network layer, access nodes take either decentralized decisions or are managed by a central entity to reduce interference. The methods of the second type focus on enabling cooperative multi-point (CoMP) transmissions, a promising medium access control (MAC) layer interference coordination scheme but with large computational burden and backhauling requirements. These methods use the network layer perspective to efficiently reduce the set of cooperating access nodes, hence alleviating the previous drawbacks of CoMP, by creating clusters. Second, we present mobility management schemes, which either use context information to anticipate handovers and future demands, or use radio fingerprints to efficiently discover SCs. Finally, we extract the main conclusions and highlight some future challenges.

II. Resource and interference management in the network layer

In this section, we present several coordination alternatives to mitigate interference impact. Most of these techniques require the coordination of the neighbor base stations (BSs) to prevent the use of the same resources in some damaging situations, e.g., for cell-edge users. This implies that the resource allocation must be influenced by these techniques, which, at the same time, have to take into account how the resources should be allocated to users. In particular, short coverage ranges imply low delay spreads, which leads to large coherence bandwidths. In this context, we investigated if a given frequency resource, W, should be dedicated, shared, or partly dedicated and partly shared between a given set of users at a given time instant (see [4][5] and references therein for further details). When compared to [5], we do not require the feedback of channel state information (CSI) at the transmitter, and only the receiver possesses CSI. Figure 1 shows some simulation results for a two-user, two-BS scenario where, at low signal to noise ratios (SNRs), sharing the same frequency resources between users is superior in terms of the long term throughput with continuous data transmission. This is due to the fact that the achievable rate is mainly limited by noise, and interference has a lower impact. At high SNRs, dedicating resources is better, since, in this case, noise becomes negligible compared to interference, and the long term throughput for sharing the resources becomes independent of the SNR [4]. Any other ratio of dedicated and shared resources is suboptimal.

The rest of this section focuses on the interference coordination techniques. These techniques are classified in a) standalone techniques in which BSs autonomously mitigate interference, b) techniques in which BSs autonomously decide to transmit in certain resources after coordinating with the neighbors, and c) centralized techniques that require a central entity. These classes are described in the following subsections. In particular, classes a) and b) are described in the first subsection, and class c) in the second subsection.

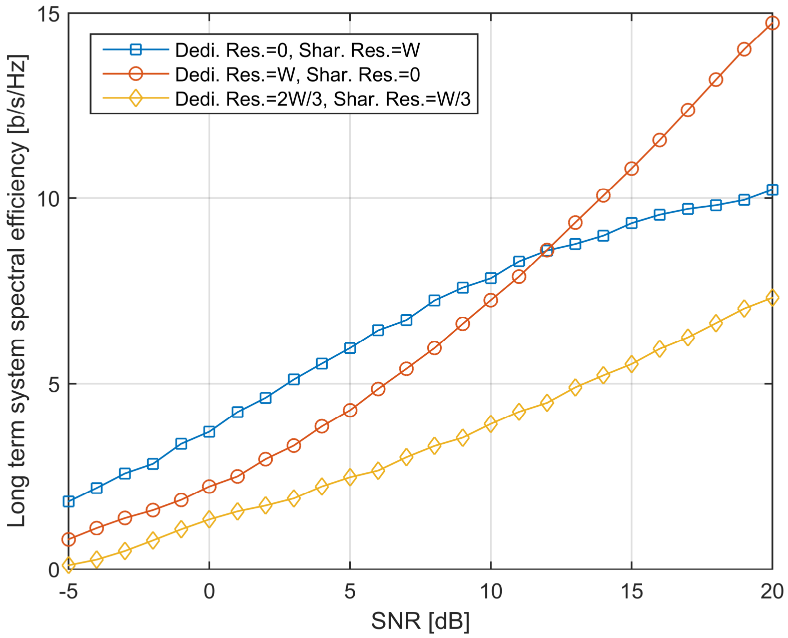

Figure 1. Long term system efficiency versus SNR. The legend shows the distribution of the total frequency resource, W, as shared, dedicated or partly dedicated or shared.

A. Decentralized interference coordination

The simplest way to deal with interference is the use of standalone interference mitigation techniques. The main interest of these techniques is that they can be implemented progressively, i.e., BSs that implement these techniques can coexist with other BSs that do not implement them. Standalone methods are based on a combination of advanced receiver side signal processing, implicit interference coordination, and scheduling. The network may enable interference mitigation using advanced receivers by, e.g., a fully synchronized network among multiple SCs. Additionally, BSs have the freedom to perform implicit coordination using interference estimation and making self-decisions on the extent of resource usage [6]. Moreover, interference-aware scheduling uses interference knowledge from the previous time slots to opportunistically schedule users that relatively experience low interference levels.

Other decentralized interference mitigation techniques require the coordination of BSs. Some of these techniques have been proposed for cellular systems, including inter-cell interference cancellation (ICIC) proposed for LTE, and enhanced ICIC (eICIC) based on almost blank subframes (ABSF) introduced in LTE-Advanced [7]. ICIC based schemes, introduced to mitigate the interference between the neighboring cells in homogeneous networks, divide the available resources into frequency bands with different transmit power profiles to create a fractional frequency reuse pattern. However, finding sufficient power profiles for networks with very heterogeneous deployments, like 5G-UDNs, is challenging. As an alternative, we proposed the use of distributed and dynamic fractional frequency reuse schemes in which the power profiles are generated dynamically [8]. To this aim, BSs select a subset of *preferential* resources to be used at full power. Then, BSs that wake up follow these steps: a) detect all interfering BSs, b) communicate with them and ask for their preferential resources, c) select its preferential resources such that they do not intersect with those of the interfering BSs, and d) report the selected resources to the interfering BSs. After step d), the BS has the highest priority to use its preferential resources, and it can, for instance, forbid their use to the interfering BSs.

The other state-of-the-art technique – eICIC based on ABSF – is a simple approach that can be applied to a very dense heterogeneous network. To overcome the disadvantage of ICIC, which is the high complexity of finding good power profiles for dense heterogeneous deployments, time-domain muting of macro BS transmission is introduced. This is motivated by the significant inter-tier interference that arises when large amounts of users are offloaded from macro layer to the small BSs using the range expansion mechanism. The muting is implemented with ABSFs that allow macro interference-free transmission gaps in the small cells. This enables the small cell scheduler to allocate resources to cell-edge users that experience the highest interference in normal mode.

Although many variants of eICIC have been introduced, they address only the macro-to-small-cells interference problem. Moreover, eICIC is usually considered in a static or semi-static form [7], and hence it cannot adapt to changing environments, thus neglecting the possible gains from frequency diversity. The dynamic application of eICIC, on the other hand, requires the availability of timely inputs of coordination data based on the network analysis, thus making this approach difficult to realize practically, because of the changing nature of radio environment.

To account for the changes in propagation conditions, our decentralized adaptive multi-tier interference mitigation [9] instead applies a game theoretic approach, where BSs select an action (resource allocation strategy) based on a probability distribution. The probabilities of particular actions are obtained using the iterative regret-matching learning procedure [10],

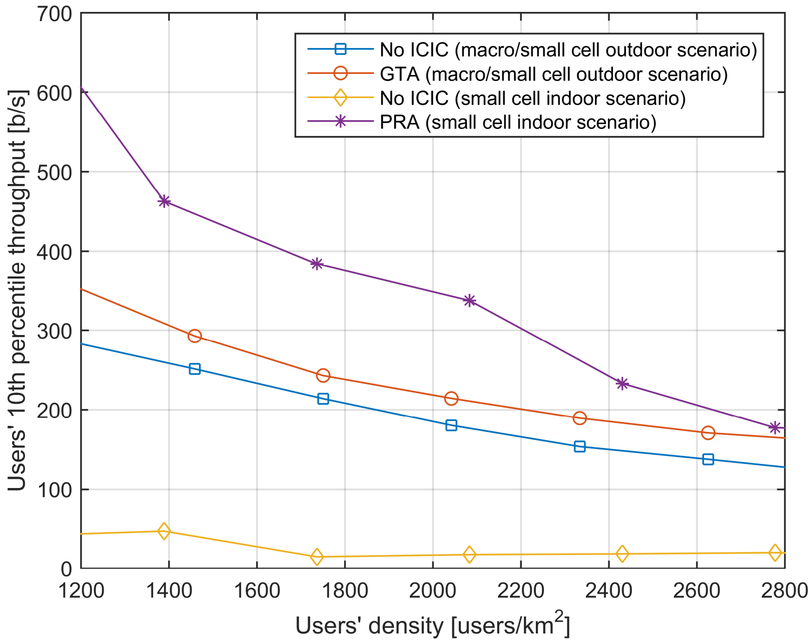

Figure 2. The 10th percentile of the users' rate for different decentralized interference coordination techniques simulated in an indoor SC scenario consisting of a 6-floor building with 10 SCs per floor and an outdoor urban scenario with 3 macro BS and 21 SCs .

where BSs learn the action regrets and aim at minimizing the average regret. The actions represent the time-frequency partitioning of resources between BSs and the transmit power, thus combining the properties of ICIC and eICIC. The regret-matching procedure is facilitated by periodic information exchange on interference and selected actions. The game aim is to cooperatively maximize a rate-based utility for all users.

The performance of our preferential resources approach (PRA) in a scenario with indoor SCs and our game theoretic approach (GTA) in a scenario with outdoor macro and SCs, both evaluated using a system-level simulation, is depicted in Figure 2. Owing to the interference-limited condition of the indoor scenario, significant gains are obtained by the PRA in the 10th percentile rate with respect to no ICIC, at expenses of a small reduction in total average throughput. In the outdoor case, a 30% gain is achieved by the GTA together with an increment of the total average throughput.

B. Centralized interference coordination

In the previous section we presented techniques that deal with interference in a decentralized manner. This section analyzes centralized techniques that have a wider perspective of interference.

A promising approach is the use of joint schedulers which, among other functions, decide the time and frequency resources used for uplink and downlink transmissions in each SC. The joint schedulers coordinate interference by muting cells at a resource block level, perform flexible uplink and downlink switching for a group of coordinating SCs, and assign resource blocks to users. One main benefit of centralized scheduling is that the algorithm can include fairness metrics for all the users within the cluster of coordinating cells.

Macro BSs are good candidates for central entities that manage the interference of their SCs. New system architectures have been proposed for this type of scenarios. In particular, the phantom cell concept takes advantage of both macro BSs broad network coverage and SCs high capacity. In this case, each user in the system is connected to both a macro BS, providing control plane connectivity, and a SC, providing user plane connectivity. This dual connectivity feature offers the possibility to flexibly deactivate unused or underutilized SCs without disrupting connectivity to the cellular network thanks to the macro BS. In addition to the network energy saving, the deactivation of SCs is beneficial in terms of interference for two main reasons. First, unused SCs transmit pilot and reference signals that interfere neighboring SCs. Second, underutilized SCs use a lot of power to transmit to a few users that could be served by neighboring SCs or even the macro BS. With this idea in mind, we proposed the following four activation and deactivation schemes:

- A downlink signaling-based scheme, in which users can discover deactivated SCs from discovery signals sent at a very low rate compared to activated SCs.
- An uplink signaling-based scheme, in which users send wake-up signals to activate and make SCs discoverable. In these two schemes, SCs are deactivated if they serve no user for certain period of time.

- A database-aided scheme, in which cached estimates of the user-small-cell channels are stored in a database so that, using users' location information, the macro BSs activate or deactivate certain SCs if necessary.
- A graph-based scheme, in which dynamic activation and deactivation is decided based on a wireless network graph.

In all the schemes presented here, resources are managed by a joint scheduler in the macro BS, which is connected to the SCs by a backhaul link. In the graph-based scheme, the macro BS monitors reports from both SCs and users to generate a wireless network graph that takes into account the users in the SCs coverage area and the overlap of their transmission ranges. The deactivation of SCs is triggered when the coverage overlap is high and the capacity usage ratio estimated from the reports is low. On the other hand, the activation of SCs is triggered in the case of low coverage, low channel quality indicators, or even high blocking probability.

Figure 3 illustrates the energy saving achieved by the downlink signaling-based, the uplink signaling-based, and the database-aided schemes measured with respect to a scheme in which SCs are always active. These results are obtained by performing system-level simulations of a single macro cell site with a cell radius of 290 m, comprised of 3 macro cells, with 20 SCs deployed per macro cell. Interested readers may find results and performance analysis of the graph-based scheme in [3].

The highest energy saving, more than 45%, is obtained with the database-aided and the downlink signaling-based schemes. The uplink signaling-based scheme consumes more energy due to the temporal activation of all SCs in the vicinity of the users that send a wake-up signal. In addition to the energy savings, the average user throughput increases due to lower interference levels. Up to 25% of throughput improvement is observed with the downlink and

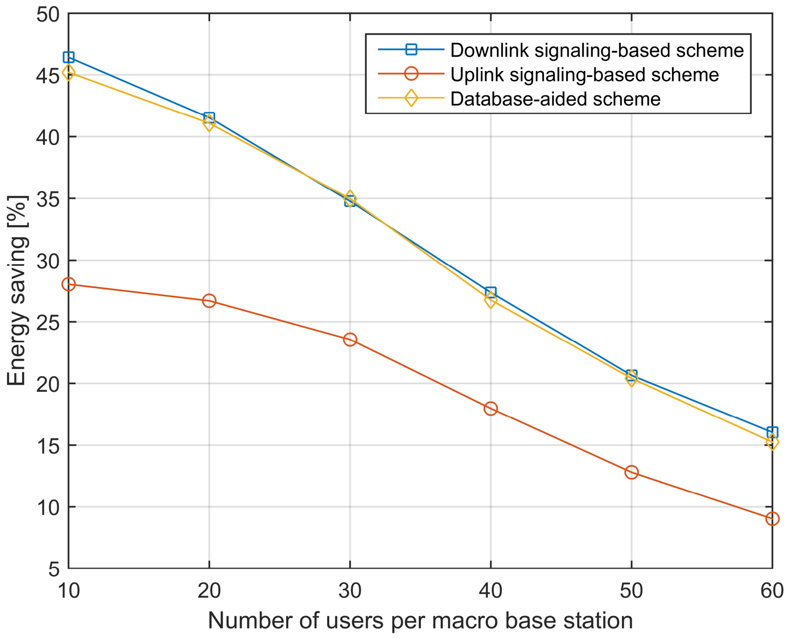

Figure 3. Energy saving achieved with the downlink signaling-based, the uplink signaling-based and the database-aided schemes.

uplink signaling-based schemes, and up to 8% with the database-aided scheme. This difference is due to the cached averaged channel estimates used by the databased-aided scheme, instead of the actual channel estimation performed by the other two schemes.

III. Clustering for CoMP

An important technology in future 5G networks is CoMP in which several BSs cooperate in serving a group of users. This cooperation is especially beneficial for the cell-edge users, since it reduces interference and increases the useful signal power. Although CoMP is a promising MAC layer interference coordination scheme, it suffers from large computational burden and backhauling requirements. This section analyzes cell clustering techniques that enable manageable CoMP by reducing the amount of cooperating points.

Cells clusters can be designed during the network deployment phase. However, the activation/deactivation and potential mobility of SCs modifies the optimum clustering, and the cluster-edge users suffer from interference like previous cell-edge users. These limitations show that advanced clustering techniques need to be carefully developed.

Taking into account the previous limitations, we proposed two clustering techniques. The first one is a user-centric dynamic clustering which creates a cluster of BSs for each individual user. This is achieved selecting the power that BSs use in the transmission of each user with the objective of reducing interference and maximizing the users' fairness. The technique uses reports of path loss and shadowing to perform the optimization, and hence, it is dynamic and adapts to network changes. It also eliminates the cluster-edge users, since all of them are in the center of their own cluster.

The second technique creates a fixed set of overlapped clusters. In particular, BSs belong to some specific number of clusters, say N, in such a way that every location in the scenario is close to the center of a cluster. This criterion also eliminates the cluster-edge users. The available resources are split into N orthogonal pools to prevent interference between overlapped clusters. The clusters are designed in the deployment phase and, hence, are not dynamic, although, since all locations are close to cluster centers, this technique has a good behavior with respect to users' mobility. In our approach, the clustering was performed in N phases in which non-overlapped clusters were generated in each one. To do this non-overlapped clustering, we designed a clustering toolbox based on graph partitioning. In particular, the toolbox generates a graph of the network in which the cells are the graph nodes, and two nodes are linked with an edge if they share certain coverage area. In each phase, the toolbox first identifies a group of head nodes selected according to their degree (number of edges incident to the node), and then forms the clusters based on the network density and by a process of "preferential attachment," where nodes prefer to join the more "popular" clusters. In each phase, we modified the graph eliminating certain edges in order to ensure that the toolbox selects a different group of head nodes.

The performance of the two clustering techniques presented in this section is depicted in Figure 4. The results are obtained by means of system-level simulations of 100 BSs and 1000 users

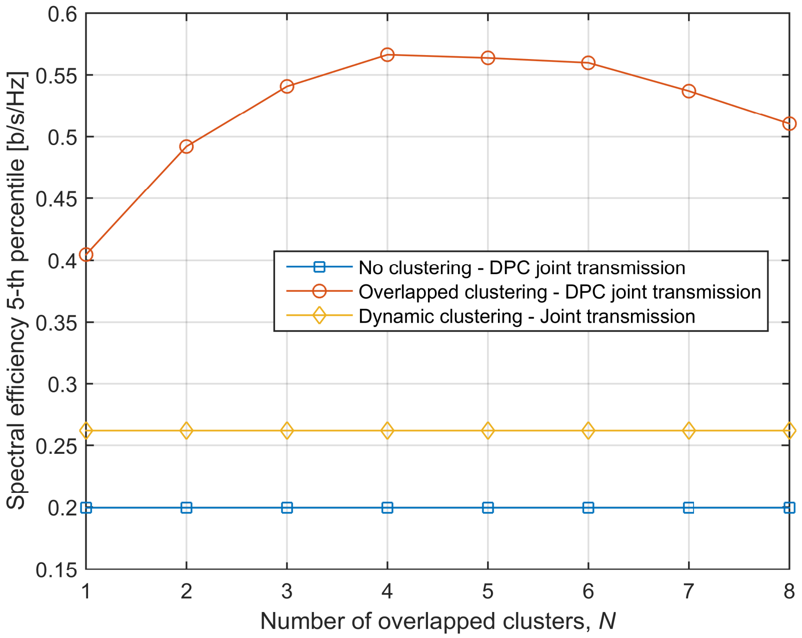

Figure 4. Spectral efficiency achieved by the 95% of users with different clustering techniques.

randomly deployed in a squared area of 500 m side. In the case of the overlapped clustering, each cluster maximized the users' fairness using joint transmission with dirty paper coding (DPC) [11] that reduces the intra-cluster interference. In the case of the dynamic clustering, DPC was not used since only one user is in each cluster. The spectral efficiency achieved by the 95% of users with the overlapped clustering is up to 3 times higher than that achieved with no clustering. The different performance of the overlapped and the dynamic clustering approaches is a consequence of the interference mitigation of DPC in the overlapped clustering.

IV. Mobility management in the network layer

Interference and mobility management are, probably, the two most challenging topics of UDNs. In this section, we will focus on mobility management, and in particular, on a new generation of handover techniques based on context information, and on energy efficient SC discovery.

A. Context-awareness for handovers

The key element of mobility management is the handover procedure, which generally utilizes well-established metrics for the handover decision, such as the reference signal received quality (RSRQ) or the reference signal received power (RSRP). However, the new challenges of 5G networks require new techniques based on context-awareness. Context refers to any information that characterizes an entity. By increasing context-awareness both on the network and user sides, the decision-making can be more distributed in forthcoming mobile networks' architectures. The fundamental context-related processes comprise monitoring, aggregating, modeling, interpreting/reasoning, storing, retrieving, and finally utilizing the context. In some cases, additional operations such as predicting the context may apply. The price to pay is that the context has to be signaled through the air interface, consuming valuable resources. However, this is usually not a show stopper as the required amount of resources is almost negligible as compared with interference coordination and, specially, CoMP. With respect to context information for handovers, the users' localization is important, and also the prediction of cells that will be traversed by the users. Other relevant context information is the RSRP, the RSRQ, the battery-level, the speed, the service type and user preferences.

Several schemes have been proposed so far that attempt to enhance the handover procedure (see a survey in [12]). These schemes extend from very simple solutions that do not attempt to acquire a holistic picture of the network environment context (in order to avoid signaling overhead issues) to complex frameworks, which however require major modifications in the core network components. We recently proposed the COmpAsS scheme for handovers [13], which is a context-aware technique executed in the user equipments that employs the user preferences, equipment capabilities and status, and the network availability, load and policies. The advantages of this approach are:

- A per-traffic-flow handover decision that enables very high service-level granularity.
- The mechanism is functioning on the terminal-side only (maintaining however the core network as the final decision-maker).
- It does not require modifications in the current 3GPP release network architecture.
- The scheme uses fuzzy logic in order to evaluate the available information resulting in a very lightweight and efficient solution for 5G networks.

The use of context information is especially useful in networks with nomadic relays, i.e., vehicle mounted relays. They extend the legacy network by randomly located relays that are not controllable by the network operators. This requires a high effort in coordination and management. In particular,

- for the handovers of the nomadic cells, a dynamic backhaul selection based on network load and backhaul quality can benefit the network performance; and
- for the users that are connected to the nomadic cells, a handover is required when the nomadic cells become unavailable, even if the user is stationary.

For the handover of users connected to nomadic cells, we proposed to solve an optimization problem based on diverse network utilities [14]. The context information about the availability of the nomadic cells can facilitate a novel class of user handover mechanisms. In particular, we proposed a predictive handover mechanism initiated by the nomadic cells based on an availability prediction in the following time slots.

Figure 5 shows the performance of our nomadic cell initiated handover (NCIH) and COmpAsS schemes. The NCIH scheme was compared against the user's RSRP based handover scheme in LTE, which required that users re-connect to the network when a nomadic cell is deactivated. Simulations were performed in a scenario with 7 BSs, 150 users and different quantities of nomadic relays that randomly became available/unavailable. The COmpAsS scheme was compared against the A2-A4 RSRQ mechanism for LTE. The scenario for the COmpAsS evaluation

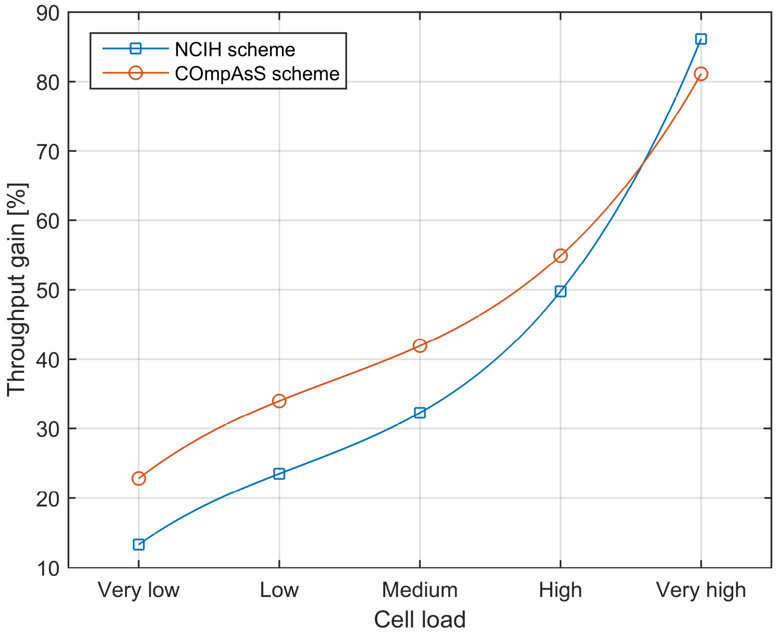

Figure 5. Throughput gains of context-aware handover schemes.

was a shopping mall with 3 floors, 50 SCs per floor, 2 eNodeBs outside the shopping mall and 100 users moving with random patterns inside the mall. The figure shows the throughput gain, which ranges from 12% to 86%, for both schemes when the traffic load increases.

Context information can be also used for load balancing. Traditional load balancing schemes either rely solely on the user (when it is in idle state) or on the network (when the user is in active state), with no actual interaction between both parties, which leads to an inefficient operation. In this context, we proposed a new family of load balancing solutions in which BSs constantly broadcast an indication of the experienced cell load that combines several factors, which is used as context information. Idle users can use these indications as additional inputs to the cell selection and reselection algorithms. In the case of active users, they can report to the serving cell the neighbor cell load indications. These cell loads can, therefore, be exploited by actual network-based handover algorithms to take into account the loads of the different target cells. Having knowledge of the neighbor cell loads allows the network to perform consistent load balancing strategies without complex information exchange between the target nodes. Here, the challenge to balance the efficiency of broadcast information transmission versus the amount and frequency of updates is not hard to achieve, because cell load usually evolves at a rather slow pace compared to the typical time scales of RRM mechanisms.

B. SCs discovery

The spectrum available for the future 5G networks will likely have separate pieces of the centimeter and millimeter bands. In order to reduce the complexity of the filter design, BSs may only operate in one of those pieces. However, the detection of SCs in many frequency bands is very challenging. To address this problem, we proposed a solution where users are assisted by

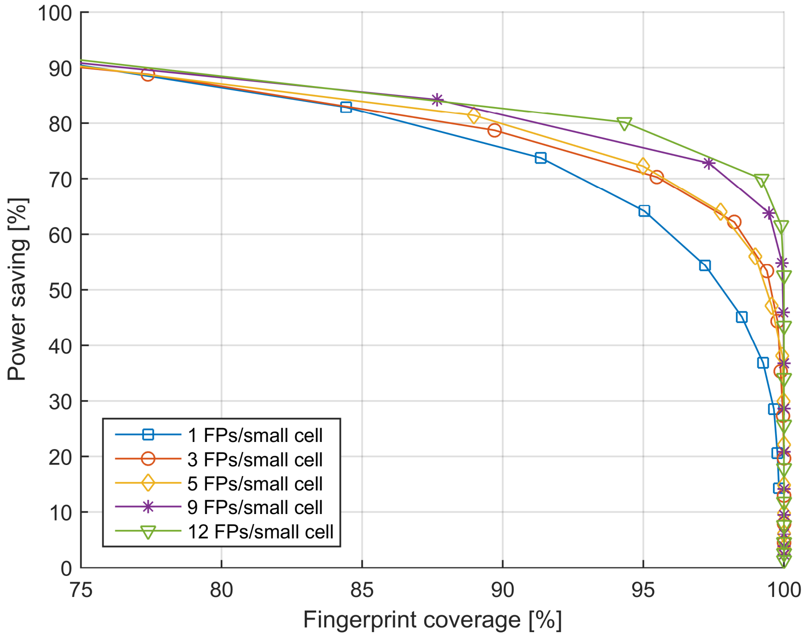

Figure 6. Simulation results showing trade-off between UE's inter-frequency measurement power saving and fingerprint (FP) coverage (percentage of area with a fingerprint match out of total SC coverage). The reference for UE power saving is periodic measurements of inter-frequency SC carrier according to LTE-A assumptions.

the network with information, which consists on radio fingerprint samples that correspond to SC locations. Radio fingerprint samples are lists of cell-ID and, e.g., RSRP interval pairs. When served by the macro cell network, as part of the normal operation, users perform neighbor cell measurements and compare those to the radio fingerprint samples. If they find a fingerprint match, they report it to the network, which configures the users with the targeted measurements (on a specific carrier) to find the corresponding SC. The benefit of this approach is that the users and the network save energy, since users avoid unnecessary measurements if no SC is in proximity, and the network activates the SCs only in the presence of users [15].

Figure 6 illustrates the power saving with respect to the percentage of the SC range covered by the fingerprints, and for a different quantity of fingerprint samples per SC. The results are obtained by means of simulations in an urban scenario with a 3-sector macro cell and 12 SCs covering approximately 20% of the outdoor area. Using 3 to 12 fingerprint samples per SC, the user energy consumption is reduced by 70 to 80% while still maintaining 95% accuracy of SC coverage. For a given number of fingerprint samples per SC, different trade-offs between fingerprint coverage and power saving have been obtained by increasing or reducing the RSRP interval where the fingerprints are considered matching.

V. Conclusions

In this article, we have presented the most promising solutions identified in the METIS project to enable cell densification in the future 5G UDNs. In particular, we presented resource and interference management techniques of different implementation complexities: standalone, decentralized and centralized. We also proposed clustering techniques to enable advanced CoMP communications, and used context information in the design of reliable and energy efficient mobility management.

Our results show that PRA can improve the throughput of the users with the worst channel conditions by a factor of around x10, and CoMP combined with an overlapped clustering by a factor of x3. Throughputs gains of 80% are also possible with our context-aware COmpAsS and NCIH mobility management techniques. With respect to energy efficiency, up to the 45% of the energy can be saved with our SC activation/deactivation techniques, and between 70 to 80% with our SC discovery technique.

Combinations of these techniques will facilitate the design of a technology that will be robust against unplanned dense deployments and user and cell mobility, although the best combination for each scenario is still an open issue. Other questions that need to be answered during the 5G system design include the extent of resource and interference management performed in the network and MAC layers, as well as the optimum amount of context information to be exchanged in order to take advantage of it and maintain low levels of signaling overhead.

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