Interference Coordination for Dense Wireless Networks

Soret, Beatriz; Pedersen, Klaus I.; Jørgensen, Niels T.K.; Lopez, Victor Fernandez

Published in:
I E E E Communications Magazine

DOI (link to publication from Publisher):
10.1109/MCOM.2015.7010522

Publication date:
2015

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Soret, B., Pedersen, K. I., Jørgensen, N. T. K., & Lopez, V. F. (2015). Interference Coordination for Dense Wireless Networks. *I E E E Communications Magazine*, *53*(1), 102-109. https://doi.org/10.1109/MCOM.2015.7010522

Interference Coordination for Dense Wireless Networks

Beatriz Soret, Klaus I. Pedersen, Niels T. K. Jørgensen, and Víctor Fernández-López

ABSTRACT

The promise of ubiquitous and super-fast connectivity for the upcoming years will be in large part fulfilled by the addition of base stations and spectral aggregation. The resulting very dense networks (DenseNets) will face a number of technical challenges. Among others, the interference emerges as an old acquaintance with new significance. As a matter of fact, the interference conditions and the role of aggressor and victim depend to a large extent on the density and the scenario. To illustrate this, downlink interference statistics for different 3GPP simulation scenarios and a more irregular and dense deployment in Tokyo are compared. Evolution to DenseNets offers new opportunities for further development of downlink interference cooperation techniques. Various mechanisms in LTE and LTE-Advanced are revisited. Some techniques try to anticipate the future in a proactive way, whereas others simply react to an identified interference problem. As an example, we propose two algorithms to apply time domain and frequency domain small cell interference coordination in a DenseNet.

INTRODUCTION

Adding base stations has historically been the most important factor for increasing the capacity of cellular networks, and it is expected to persist in the upcoming years. Mobile operators are finding that very high traffic demands are typically concentrated in small geographical areas. To cope with this, small cells are the best match, since they can be opportunistically deployed in the hotspots, in a highly irregular way. Consequently, base station densification is going to be dominated by small cells. Besides that, taking new spectrum bands into use and techniques for efficient spectrum utilization will contribute to reach the challenging capacity targets. These very dense networks (DenseNets) can be seen as a natural evolution of today's Heterogeneous Networks (HetNets) [1, 2], inheriting most of their pros and cons.

However, DenseNets are also accompanied by a number of new challenges to be addressed. For example, backhaul will rise in importance [3]. With densification, the goal of operators is to deliver additional capacity and coverage with sufficient backhaul capacity and low latency without recurring operational expenditure (OPEX) charges, with solutions that range from fiber and Ethernet to wireless. Another important issue is mobility. Dense deployment of eNBs is challenging in a high-speed mobile environment, where frequent handovers may degrade the performance of the network. Numerous mobility enhancements and corresponding analyses have been studied in the context of HetNets [4, 5], and the investigations are expected to continue for DenseNets. The focus of this paper is the omnipresent interference, and how to combat it. Inter-cell interference is identified as the major limiting factor in Long Term Evolution (LTE) networks. Diverse interference management techniques have been included through successive releases of the LTE standard, from Rel. 8 to the latest completed Rel. 11. For example, solutions for interference coordination within the macro layer range from simple frequency domain methods [6] to more advanced coordinated multi-point (CoMP) techniques [7]. In the context of LTE HetNets, cross-tier interference (between the macro layer and the small cell layer) has been extensively investigated in the literature (e.g. [8]). With the anticipated small cell densification, the 3GPP work continues in Rel. 12 to have additional small cell enhancements [9], as well as coordinated multi-cell packet scheduling methods, referred to as enhanced CoMP.

The focus of this paper is on downlink interference, which becomes trickier in a dense deployment, with a more diffuse definition of aggressor cell and victim user. Here new techniques to deal with the co-tier interference are needed. In addition to network-based strategies relying on coordination among eNBs, advanced user equipments (UEs) will be equipped with interference cancellation capabilities that can further benefit from the knowledge about interfering transmissions under possible coordination by the network. Moreover, the mitigation techniques must be sufficiently dynamic to capture the variations of the interference, which can be very pronounced in a DenseNet where each cell serves a low number of users. For instance, we propose new time and frequency domain coordination strategies for dense clusters of small cells. The main idea is to have a proper resource division (time or frequency) by dynamically estimating the potential of the partitioning.

Beatriz Soret and Klaus I. Pedersen are with Nokia Networks.

Klaus I. Pedersen, Niels T.K. Jørgensen and Víctor Fernández-López are with Aalborg University.

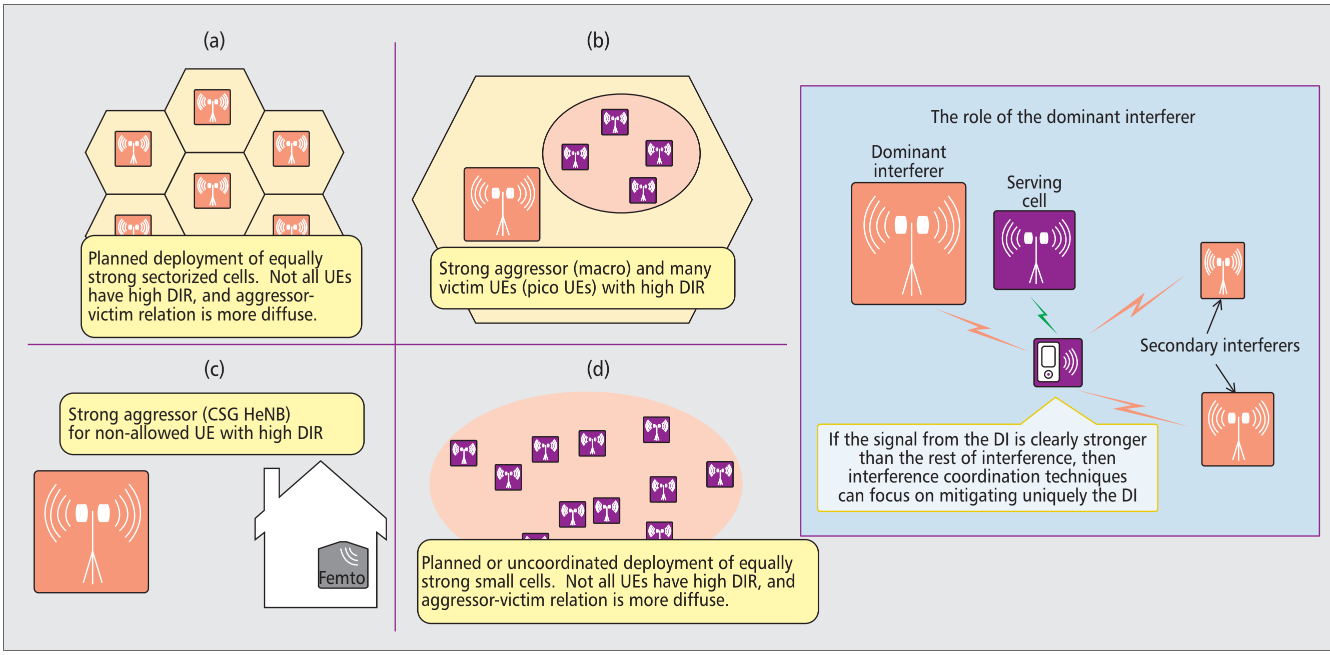

Figure 1. Interference scenarios and the role of the DI.

The rest of the paper is organized as follows. We first present the interference distribution in different 3GPP scenarios and a site-specific case in Tokyo, noting that the relation between aggressor and victim and the predominance of an interferer depend heavily on the particular scenario. Second, we give an overview of the available interference management methods. With more spread interference, there is still need for further development of inter-cell interference coordination (ICIC) techniques. We propose two solutions for the time and frequency domain small cell interference coordination, relying on either proactive or reactive schemes. In both cases, system level performance results are presented to demonstrate the benefits of small cell coordination in terms of higher end-user experienced throughput and lower outage probability. The article closes with concluding remarks.

Interference Scenarios and Statistics

Downlink interference can be mitigated from the network side by partially muting the interfering cells through a coordinated inter-cell algorithm. Another possibility is to let the UEs combat part of the interference by means of advanced receivers with interference cancellation (or suppression) capabilities. In any case, the choice of a proper interference management technique calls for a thorough study of the interference distribution between base stations and mobile users, where the interference sources for a UE are sorted from the strongest, the dominant interferer (DI), to the weakest. A good metric capturing the predominance of a single dominant interference is the dominant interference ratio (DIR), defined as the ratio between the DI and the rest of the perceived interference, shown mathematically as

$$DIR = \frac{I_{strongest}}{\sum_{i \neq strongest} I_i + N} \tag{1}$$

where $I_{strongest}$ is the power received from the DI, I_i is the power received from interferer i, and N is the thermal noise power. The improvement in signal to interference and noise ratio (SINR) from ideal interference cancellation of the DI is proportional to the DIR, giving a fine estimation of whether the strategy can focus uniquely on the DI, or if weaker interferers also need to be cancelled or suppressed. The quantities in Eq. 1 are time-variant, so the benefit from mitigating the DI is only fully achieved when conducted on a per-user basis and dynamic in time.

To illustrate the variation of the interference relations with the network topology, Fig. 1 draws four exemplary scenarios. Figure 1a is the traditional homogeneous network, deployed in a planned manner with equally strong sectorized macro cells, where not all the UEs perceive a high DIR and hence the aggressor-victim relation is diffuse. On the contrary, in a co-channel HetNet composed of macros and outdoor small cells sharing the same carrier (Fig. 1b), the macro cells are the clear aggressor for most of the small cell users, which are subject to strong downlink interference both in data transmission and control channels [8]. Another option is the deployment of indoor closed subscriber group (CSG) home eNB small cells (Fig. 1c), where macro users not belonging to the group cannot connect. Here, the small cell plays the role of aggressor to nearby indoor macro users that are not allowed to get service from the home eNB, resulting in so-called macro coverage holes. Also in this case, the definition of aggressor and victim is precise. Finally, small cells (indoor or outdoor) can be deployed on a dedicated carrier in a planned or unplanned manner (Fig. 1d), with

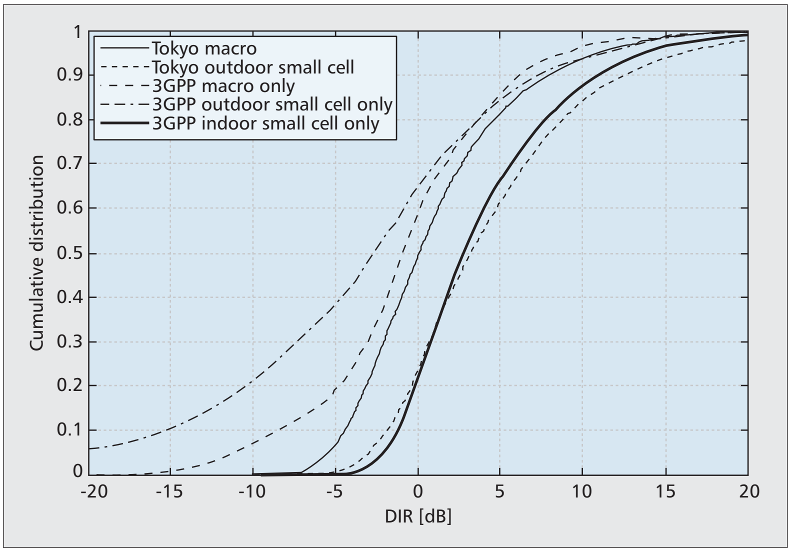

Figure 2. CDF of the DIR in different scenarios.

equally strong small cells and omni directional antennas. Similarly as for the homogeneous macro networks, not all UEs have a clear DI and the aggressor-victim relation is vaguer. Another factor is the potentially unplanned (and irregular) nature of this topology, which increases the probability of experiencing a high DIR.

To sum up, deployments of equally strong cells tend to experience a spread interference map (*co-tier interference*), where users do not necessarily perceive a clear aggressor or DI, but often multiple interfering signals of similar strength. The situation is exacerbated with densification: as the number of base stations per square meter increases, the chances of experiencing interference from more than one source also increase. On the other hand, interference between different layers (*cross-tier interference*) leads to higher values of DIR and has been widely investigated for HetNets. Finally, it is more likely to perceive a DI in more irregular deployments. With a high DIR, the benefit of applying some interference coordination or mitigation mechanism is obtained by focusing uniquely on the dominant interferer, while scenarios with low DIR are more challenging and need to deal with several interference sources.

In order to further illustrate the characteristics of different network deployments, Fig. 2 compares the empirical cumulative distribution function (CDF) of the DIR for various scenarios. Three generic 3GPP simulation scenarios as defined in [9] are considered, based on commonly accepted stochastic propagation models. The 3GPP macro-only deployment is composed of a regular grid of three-sector base stations deployed at 2 GHz, i.e. similar to the scenario in Fig. 1a. The 3GPP scenarios with clusters of small cells operate at 3.5 GHz. For the outdoor case, 10 small cells are randomly deployed in circular hotspot areas of 50 m radius. For the indoor case, a dual stripe multi-floor building block with one small cell per 100 m^2 apartment is assumed. In addition to the results from the standardized 3GPP cases, we also report results for a specific deployment in the city of Tokyo, Japan. Interference statistics are extracted for an area of approximately 1 km^2 around the Kinshicho Station. The buildings in this deployment area have an average height of 24 m and a maximum of 150 m. A total of 20 macro sites are deployed at 800 MHz (three-sector), 1700 MHz (three-sector), and 2100 MHz (six-sector), and at a height of 5 m above the building in its local area. The average macro inter-site distance equals 227 m (in contrast to the 500 m of the 3GPP case) with a standard deviation of 18 m. Moreover, 100 small cells are deployed at 3.5 GHz and at 5 m height in street canyons, placed mainly near the tallest buildings where the radio signal from the elevated macro-cells typically is weaker and more traffic can be offloaded. The statistics of the Tokyo case are separated for the macro and the small cell users.

Observing the curves in Fig. 2, the lowest DIR corresponds to the 3GPP outdoor small cell case, with dense clusters and a higher probability of coinciding with several active neighbors. On the other extreme, the highest DIR is observed for the Tokyo case, due to the more irregular and dense deployment, with the DIR of the 3GPP indoor case very close to the outdoor small cell layer in Tokyo. If a DIR of 3 dB, for example, is taken as a representative high value, less than 25 percent of UEs in the 3GPP outdoor small cell case will receive a clear benefit from mitigating the strongest interferer, whereas this percentage goes up to more than 50 percent in the small cell layer of the Tokyo scenario. The main learning here is that realistic dense networks (exemplified here by the data from Tokyo) may offer higher values of the DIR, and thus the gains of applying interference coordination might be higher as compared to the 3GPP scenarios. With lower values of the DIR, mechanisms mitigating the strongest interferer should be applied only for a selected subset of users.

Overview of Interference Mitigation Techniques

Extensive research related to LTE downlink interference mitigation has been performed in academia, industry, and standardization bodies such as 3GPP. Table I shows an overview of the different mechanisms. The interference problem can be addressed from the network side, the user side, or a joint action of both. Furthermore, some techniques try to anticipate the future in a proactive way, whereas others simply react to an identified interference source. The disadvantage of reactive solutions is that in highly dynamic environments the actions may happen too late. On the other hand, proactive approaches can lead to a waste of efforts and/or resources by trying to solve matters that may never materialize.

Within the network-based interference coordination category, the first group of solutions is based on resource partitioning, which can be conducted in the space domain, time domain, or frequency domain [9]. The simplest form of space domain resource partitioning is to use higher order sectorization in the macro site installations. As an example, upgrading from three-sector to six-sector macro sites is found to offer 50–80 percent capacity improvement depending on the spatial characteristics of the environment [10]. More advanced space domain techniques include coordinated beamforming and coordinated multi-point techniques [7].

The time and frequency domain resource partitioning techniques rely on blanking certain transmission resources in some cells to improve the perceived signal quality of those resources in the neighboring cells, resulting in a capacity loss for the cells blanking resources (called cost) and a benefit for the cells with reduced interference. The optimum blanking of resources can therefore be formulated as a value maximization problem, where the value (or the net benefit) equals the benefit minus the cost. The enhanced ICIC (eICIC) scheme is an example of time domain resource partitioning for co-channel macro and small cell deployments, where some transmission resources are blanked at the macro to improve the quality of the users served by the small cells [8]. The blanking is achieved by using the so-called "almost blank subframes" (ABS). Using ABS at the macro is found to offer promising performance improvements for co-channel macro and small cell cases, as the macro acts as an aggressor for many victim small cell users, and therefore the benefit can significantly exceed the cost.

Frequency domain resource partitioning can be realized by assigning different carriers to eNBs, or by using different OFDMA sub-carriers for transmission [6]. The simplest form is hard frequency reuse, where nearby eNBs use orthogonal frequency carriers. However, hard frequency reuse seldom results in the best performance for LTE. An alternative option is fractional frequency reuse (or soft frequency reuse), where some resources are reused by all eNBs, while others are dedicated to only certain eNBs. Furthermore, autonomous eNB mechanisms for dynamically choosing the best carrier(s) have been widely investigated in the context of femto cell networks [11]. In all cases, the potential of time and/or frequency domain inter-cell partitioning methods is fully exploited when they are dynamically adjusted in step with the time-variant behavior of the system and the traffic fluctuations. As examples of the former, [12] demonstrates the benefits of fast versus slow inter-cell coordination, while aspects of centralized versus distributed coordination are examined in [13].

Finally, the adjustment of the eNB transmit power is another network-based technique that has often been applied to closed subscriber group femto cells with the goal of reducing the cross-tier interference toward co-channel macro users [14].

An alternative to network-based interference coordination is to rely on advanced UE receivers with interference mitigation capabilities [3]. UEs with multiple antennas can exploit linear interference suppression techniques such as interference rejection combining (IRC). However, its applicability is limited. A UE equipped with M antennas has M degrees of freedom: one is used for the reception of its own stream; the remaining M-1 are available to exploit either diversity or interference suppression. For example, a UE equipped with two antennas and being served by an eNB using rank two has to use its single degree of freedom for inter-stream interference suppression. Yet the linear interference suppression at the UE can be boosted with network coordination. One example is to use rank coordination. The principle is to schedule victim UEs with rank one (single stream) on transmission resources where the neighboring cells also apply rank one transmission. By enforcing such inter-cell coordination, the highest gain from using IRC at the UE can be achieved. Similarly as for the resource partitioning techniques, the use of inter-cell rank coordination and IRC receivers presents a value that can be expressed as benefit minus cost. Here the benefit is the interference suppression gain offered by IRC, while the cost is the potential loss of throughput by restricting some cells to only use rank one transmission on certain resources.

The second variant of receiver-based interference mitigation is to apply non-linear interference cancellation, where the UE reconstructs the interfering signal(s) followed by subtraction before decoding the desired signal. These techniques are especially attractive for cancelling interference from semi-static signals such as common reference signals, broadcast channel, and synchronization channels, as already supported to a large extent in the latest LTE releases. However, applying non-linear interference cancellation to data channel transmissions is much more challenging, as the scheduling and link adaptation (i.e. selection of modulation and coding scheme) are highly dynamic, and conducted independently per cell. Hence, getting the most out of non-linear interference cancellation requires additional network assistance, and it is an ongoing work topic in 3GPP Rel-12 standardization [15]. The idea is to simplify the processing at the UE by providing a priori knowledge of the interfering signal characteristics such that the blind estimation of all their features can be reduced.

The network-based and receiver-based interference mitigation techniques in Table 1 essentially address the same problem: avoiding undesirable inter-cell interference. However, they have been typically treated separately in the literature. In principle, they are not mutually exclusive, but addressing the same problem independently from different perspectives can lead to some waste of effort. It remains to be further investigated how to maximize the synergies from both strategies. Thus, the new inter-cell interference challenges should be addressed by enforcing joint multi-cell cooperation techniques to fully exploit all degrees of freedom, as illustrated in Fig. 3. Further research on scheduler and link adaptation coordination between eNBs is required, providing additional a priori knowledge to UEs for interference cancellation, as well as exploiting recent advances in receiver signal processing techniques.

Further research on scheduler and link adaptation coordination between eNBs is required, providing additional a priori knowledge to UEs for interference cancellation, as well as exploiting recent advances in receiver signal processing techniques.

Small Cell Interference Coordination for DenseNets

Within the network-based ICIC category, we propose two methods to improve the performance of dense small cell networks: one proactive method using time domain ICIC, and a

Network based resource partitioning	Spatial-domain resource partitioning	Use of spatial filtering techniques. Simplest form is use of sectorized antennas. More advanced forms include use of arrays of transmit antennas or active antennas with coordinated beamforming between cells.
	Time-domain resource partitioning	Cells are time-synchronized and coordinate at which time-instances they transmit, such that there are time-instances where Cell A can serve its users without interference from Cell B. Also known as coordinated muting. Examples include 3GPP defined techniques such as eICIC and CoMP.
	Frequency-domain resource partitioning	Include options such as using hard or soft frequency reuse between neighboring cells. The frequency-domain resource partitioning can be on PRB resolution, or on carrier resolution if having networks with multiple carriers. The latter is also referred to as carrier-based ICIC.
Network based transmit power control	Transmit power control per cell	Adjustment of transmit power per cell to improve the interference conditions. Examples include 3GPP defined techniques for femto cell transmit power calibration to reduce interference toward co-channel macro-users.
UE based interference mitigation	Interference suppression	Interference suppression by means of linear combining of received signals at the UEs antennas. Examples of such techniques are optimal combining and interference rejection combining.
	Interference cancellation	Interference cancellation with non-linear techniques where the UE estimates one or multiple interfering signals and subtracts them from the received signal, followed by detection of the desired signal. Examples include successive or parallel interference cancellation schemes.
	Network assisted interference mitigation	Schemes where the UE receives additional assistance information from the network to facilitate more efficient interference mitigation. This includes cases where the UE receives a priori information of interfering signals that it should suppress. The simplest example is common reference signal (CRS) interference cancellation (IC), where the UE receives information related to neighboring cell CRS characteristics to enable easier non-linear IC of those.
Joint network and UE based nterference mitigation	Exploiting all degrees of freedom for maximizing the system performance	Hybrid schemes with joint multi-cell coordination to maximize the benefits of both network based and UE receiver based interference mitigation techniques. One example is to use inter-cell rank coordination, such that a UE with the capability of linear interference suppression of a few strong interfering streams is primarily scheduled when its serving and interfering cells are transmitting with rank-1.

Table 1. Overview of downlink interference mitigation toolbox.

second reactive scheme that relies on carrier domain ICIC. The time domain algorithm is applied to clusters of outdoor small cells, whereas the carrier domain solution has been evaluated for indoor deployments. In both cases it is required that the algorithm adapt to changing traffic conditions, created by a dynamic birth-death traffic model with a fixed payload per call. When the payload has been successfully delivered, the call is terminated.

Proactive Time Domain ICIC

In the time domain, some subframes are muted in the small cell layer in order to mitigate the interference to the victim users. As seen in the statistics in Fig. 2, the definition of aggressor and victim is not straightforward in dense clusters of cells, and deciding which small cell to mute and when to do it is not trivial. Even within the same cell, users perceive different neighbor small cells as their main aggressor.

The muting actions are only taken if a small cell is identified as an aggressor. Otherwise, normal transmission is used. Therefore, a key aspect of the algorithm is the identification of victim users and their aggressors. With the goal of improving the coverage user throughput, defined as the 5th percentile user throughput, without compromising the average user throughput, the identification of a victim user is twofold. First, the ratio between the received signal from the serving cell and the DI has to be below a threshold (set to 10 dB in the simulations). Second, the DIR has to be above 3 dB (the DI to be perceived at least at double power as compared to the rest of interference). If both conditions are met, the user is classified as a victim user and its

DI is identified as the aggressor cell, which will be requested to mute. The muting action is reverted when the victim user that triggered a muting leaves the system.

The muting coordination among small cells is especially challenging when one small cell is simultaneously aggressor and serving a victim user. In these cases it is necessary to coordinate the muting actions among small cells to avoid situations in which the cell serving the victim user is muting at the same time as the aggressor. This coordination is attained with a proactive approach, in such a way that each cell has some pre-assigned "good" time slots with improved SINR conditions and some "bad" slots where it may be asked to mute. The pattern of these pre-assigned time-slots is set a priori. As the densification grows, it is not convenient to apply the algorithm at a full cluster level as it leads to too complex coordination, and instead coordination within subclusters of small cells is recommended. The small cell subcluster division can be done based on the past history UE measurements and/or small cell network listening mode (NLM) measurements to identify interfering cells that should belong to the same subcluster [13].

Reactive Carrier Domain ICIC

As a second example of network-based interference coordination, we present a reactive carrier domain ICIC solution. The goal is to orchestrate a proper use of the component carriers (CC) to have all users served with at least a certain minimum data rate, expressed by the guaranteed bit rate (GBR). By default, all the small cells utilize all the available CCs (reuse 1 strategy).

The identification of victim users experiencing too low service rates, i.e. below the promised GBR, is the criterion to trigger the reactive actions. If the small cell serving the victim user is not using all its CCs, it can choose to enable more CCs to increase the available bandwidth. It can also choose to request interfering small cells to stop using certain CCs to reduce the experienced interference at the victim user. For each of the possible hypotheses to improve the performance of the victim user, the corresponding value (benefit minus cost) is estimated, followed by taking the action that results in the highest positive value. As an example, the hypothesis corresponding to taking more CCs into use for the small cell serving the victim user will result in a benefit for that cell, but also a potential cost in the neighboring cells that will experience increased interference. Similarly, if a CC is switched off in cell A it will result in a performance loss (cost) for users served by cell A, while users experiencing interference from cell A will experience less interference (benefit). For the sake of simplicity, not all the possible hypotheses are evaluated, but only those that involve neighboring cells acting as a DI for the identified victim user. Finally, when a user that has previously triggered the carrier domain ICIC framework leaves the system, the prior actions aiming at improving the performance for that user can be reverted.

It is worth noting that the benefit and cost calculations require information to be shared between the small cells over the backhaul. However, the information is rather limited, and is not considered sensitive to typical backhaul latencies of 10-50 ms.

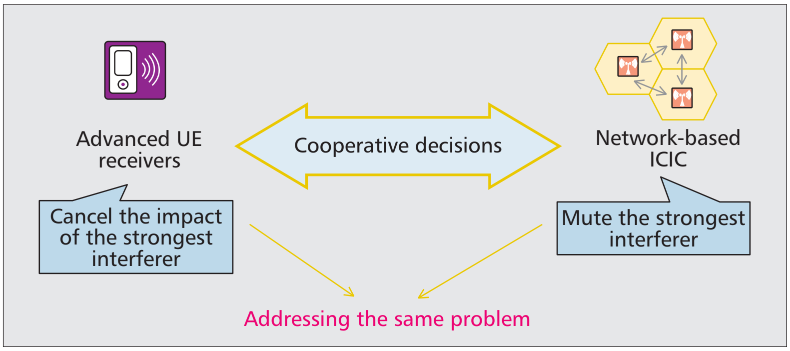

Figure 3. Cooperative network-based and UE receiver-based interference mitigation.

Performance Gains

A network layout following the guidelines in [9] is simulated. The considered 3GPP Rel-12 small cell scenarios with clustered outdoor cells and indoor cells are in line with the descriptions given for Fig. 2. For the case with outdoor clusters, we consider an ultra dense case with 12 small cells per cluster, whereas indoor small cells are in a dual stripe building block. The system-level simulator follows the LTE specifications, including detailed modeling of major radio resource management functionalities such as packet scheduling, hybrid automatic repeat request (HARQ), link adaptation, 2×2 closed loop single-user MIMO with dynamic precoding, and rank adaptation. Proportional fair (PF) scheduling is applied independently at each cell. The finite payload per user is 0.5 Mbytes. For the simulations of outdoor small cell clusters, we use an open loop traffic model with Poisson call arrivals and an average offered load per cluster area ranging from 50 Mbps to 110 Mbps. The simulations for the indoor small cell cases assume a closed-loop traffic model with a constant number of users per building block, with a new call generated immediately after an existing call is completed.

In Fig. 4a the user throughput gain of time domain ICIC is presented as a function of the offered load. As expected, the relative gain increases with the offered load of the system, both in 5 percentile and 50 percentile user throughput, going up to 40 percent and 25 percent respectively for the highest simulated load. On the other hand, no significant gains were observed for values of offered load below 50 Mbps. This makes good sense: at low load, few users are active at the same time, and the probability of experiencing strong interference from a neighbor small cell decreases. In Fig. 4b the maximum muting ratio (corresponding to the small cell muting a larger percentage of time in the simulation) and the average muting is plotted, as a function of the offered load of the system. As the offered load increases, the percentage of muting in the system also increases, since the condition triggering the muting actions is met more often.

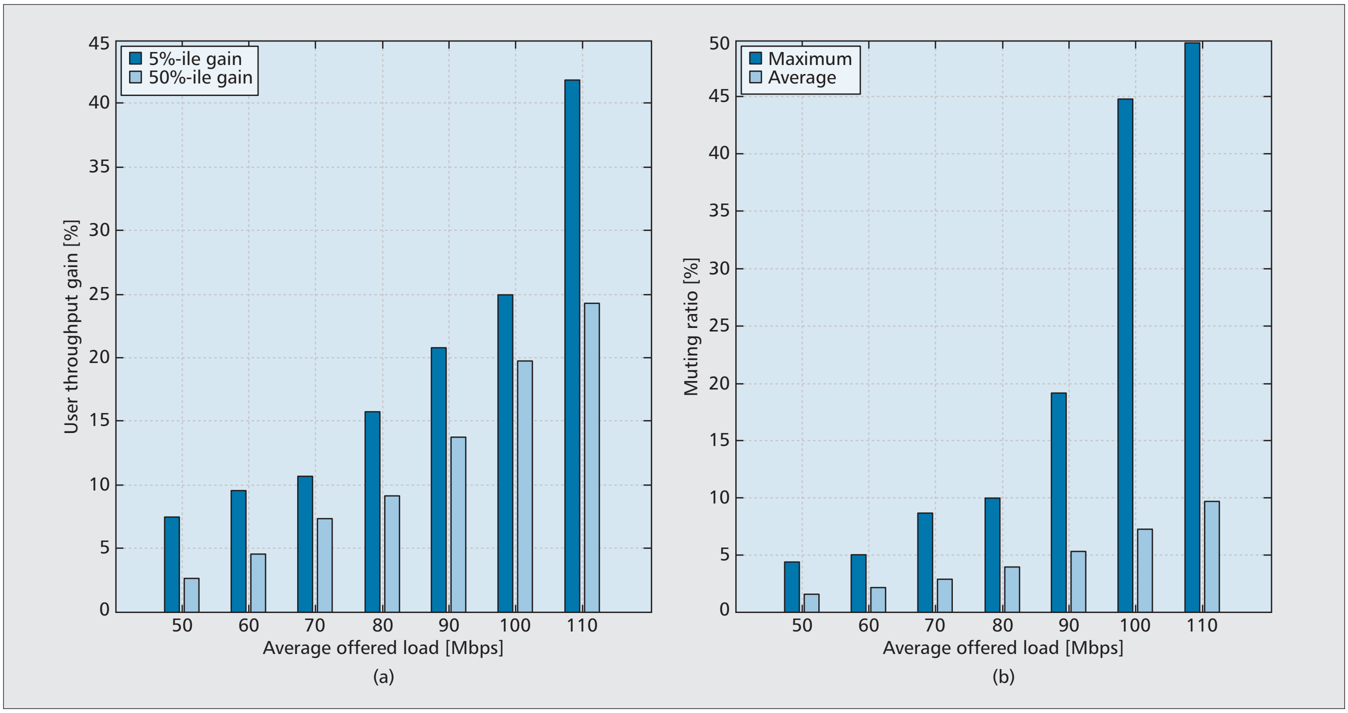

Figure 4. Time domain ICIC with outdoor small cell DenseNets: performance results: a) user throughput gain vs. average offered load; b) maximum and average muting ratio vs. average offered load.

In Fig. 5 the performance of carrier domain ICIC with four CC per small cell is shown. Figure 5a shows the outage probability of having users experiencing a service rate below their GBR versus the offered load (expressed by the average number of users per small cell). Results are reported for both the plain frequency reuse case (without any interference management) and for the proposed reactive carrier domain ICIC scheme. Similarly to the results of the time domain ICIC, there is no gain from applying interference coordination at low load with only a few users per small cell. As expected, the improvement in outage becomes significant as the load increases, allowing one more user per small cell when the carrier domain ICIC is enabled. Indeed, the increase in capacity goes up to 25 percent: four users with reuse one versus the five users of carrier domain ICIC. The probability mass function for the number of used CCs per small cell is reported in Fig. 5b for each offered load. With only one user per small cell on average, it is observed that 94 percent of the cells use all four CCs, i.e. the carrier domain ICIC is seldom triggered. As the load increases, the interference coordination is applied more often, with only 18 percent probability of using all four CCs per small cell.

Conclusions

In this paper we have discussed the role of the interference for a variety of deployments, ranging from homogeneous macro-only networks to dense small cell networks. The first step has been motivating the terminology of aggressor and victim and the dominant interference ratio (DIR), as effective elements for investigating the advisability of interference coordination. Interference statistics for generic 3GPP simulation scenarios and a site-specific case in Tokyo are compared, showing a larger potential of applying interference management techniques in the latter case. An overview of the huge variety of interference management techniques is also presented, and the best solution for a given network will depend on factors such as the deployment, the desired optimization goal, or the UE capabilities. Hybrid schemes of network-based interference coordination and user-based interference suppression by means of advanced receiver signal processing are identified as an area that requires further research. Finally, we have proposed two algorithms to apply either proactive time-domain or reactive carrier-domain co-tier interference coordination with different optimization goals. The main idea is to have a proper resource division (time or frequency) by dynamically estimating the potential of the partitioning. The performance results show gains of 25–40 percent user throughput and 25 percent in capacity. In conclusion, we have essentially shown that evolution to DenseNets opens new opportunities for interference coordination research.

Acknowledgement

The authors want to thank Laura Luque from Aalborg University for her help with the site-specific scenario.

References

[1] A. Ghosh *et al.*, "Heterogeneous Cellular Networks: From Theory to Practice," *IEEE Commun. Mag.*, vol. 50, no. 6, June 2012, pp. 54–64.

[2] J.G. Andrews, "Seven Ways that HetNets are a Cellular Paradigm Shift," *IEEE Commun. Mag.*, vol. 51, no. 3, Mar. 2013, pp. 136–44.

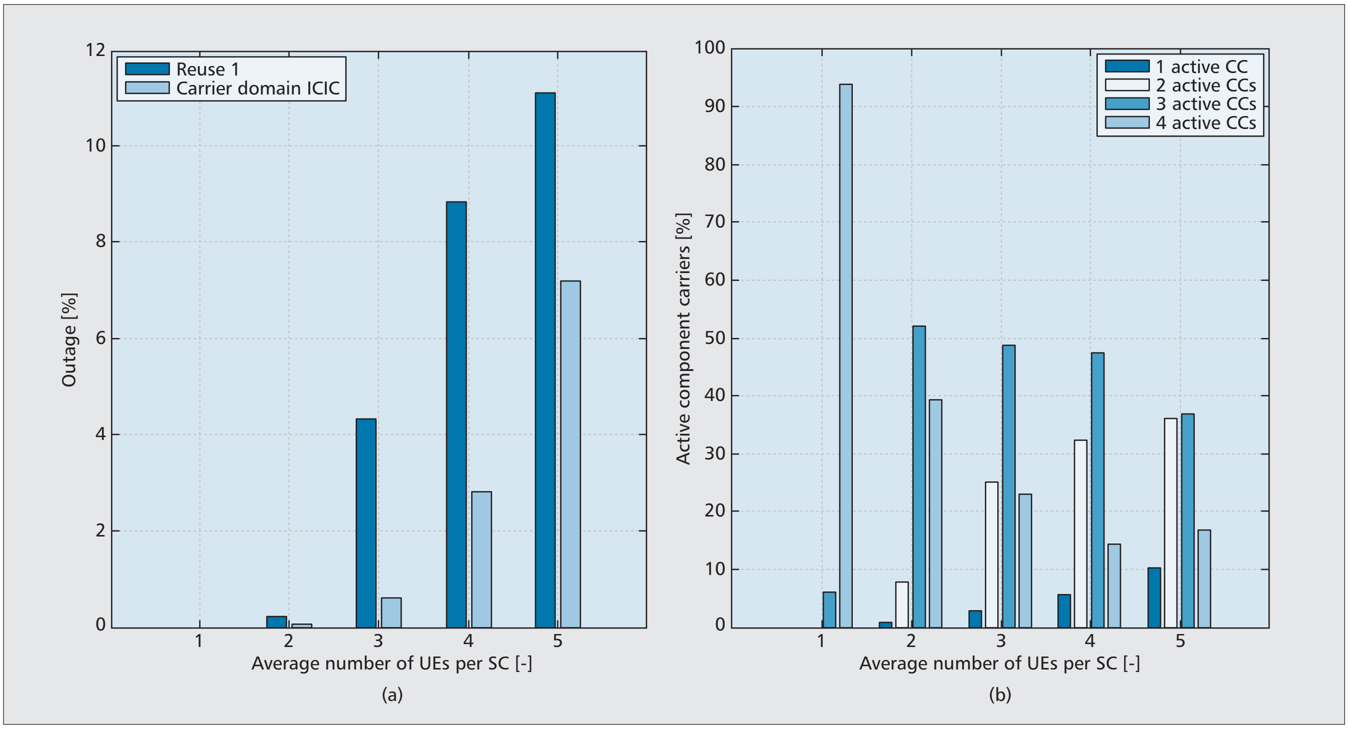

Figure 5. Carrier domain ICIC with indoor small cell DenseNets: performance results: a) outage vs. average number of UEs per small cell; b) probability mass function for the number of used CCs vs. average number of UEs per small cell.

[3] N. Bhushan *et al.*, "Network Densification: The Dominant Theme for Wireless Evolution into 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, Feb. 2014, pp. 82–89.

[4] S. Barbera *et al.*, "Improved Mobility Performance in LTE Co-Channel HetNets Through Speed Differentiated Enhancements," *IEEE Proc. Globecom, Wksp. Heterogeneous, Multi-hop, Wireless, and Mobile Networks*, Dec. 2012, pp. 426–30.

[5] A. Prasad *et al.*, "Energy-Efficient Inter-Frequency Small Cell Discovery Techniques for LTE-Advanced Heterogeneous Network Deployments," *IEEE Commun. Mag.*, vol. 51, no. 5, May 2013, pp. 72–81.

[6] G. Boudreau *et al.*, "Interference Coordination and Cancellation for 4G Networks," *IEEE Commun. Mag.*, vol. 47, no. 4, Apr. 2009, pp. 74–81.

[7] J. Lee *et al.*, "Coordinated Multipoint Transmission and Reception in LTE-Advanced Systems," *IEEE Commun. Mag.*, vol. 50, no. 11, Nov. 2012, pp. 44–50.

[8] K. I. Pedersen *et al.*, "Enhanced Inter-Cell Interference Coordination in Co-Channel Multilayer LTE-Advanced Networks," *IEEE Wireless Commun. Mag.*, vol. 20, no. 3, June 2013, pp. 120–27.

[9] 3GPP, TR 36.872 "Small Cell Enhancements for E-UTRA and E-UTRAN — Physical Layer Aspects," v. 12.0.0, Sept. 2013.

[10] S. Kumar *et al.*, "Performance Evaluation of 6-Sector-Site Deployment for Downlink UTRAN Long Term Evolution," *IEEE Proc. Vehic. Tech. Conf.*, VTC 2008-Fall, Sept. 2008.

[11] L. Garcia *et al.*, "Autonomous Component Carrier Selection for 4G Femtocells — A Fresh Look at an Old Problem," *IEEE JSAC*, vol. 30, no. 3, Apr. 2012, pp. 525–37.

[12] B. Soret *et al.*, "Fast Muting Adaptation for LTE-A HetNets with Remote Radio Heads," *IEEE Proc. Globecom*, December 2013.

[13] R. Agrawal *et al.*, "Centralized and Decentralized Coordinated Scheduling with Muting," *IEEE Proc. Vehic. Tech. Conf.*, May 2014.

[14] D. López-Pérez *et al.*, "OFDMA Femtocells: A Roadmap on Interference Avoidance," *IEEE Commun. Mag.*, vol. 47, no. 9, Sept. 2009, pp. 41–48.

[15] 3GPP, TR 36.866 "Study on Network-Assisted Interference Cancellation and Suppression (NAICS) for LTE," v. 12.0.0, Mar. 2014.

Biographies

BEATRIZ SORET (beatriz.soret@nsn.com) received her M.Sc. and Ph.D. degrees in 2002 and 2010, respectively, from Málaga University, Spain. She is currently a radio research specialist at Nokia Networks in Aalborg, Denmark. Her main research interests are related to radio resource management, heterogeneous networks, and quality of service for 4G and 5G networks.

KLAUS I. PEDERSEN (klaus.pedersen@nsn.com) received his M.Sc. E.E. and Ph.D. degrees in 1996 and 2000, respectively, from Aalborg University, Denmark. He is currently with Nokia Networks in Aalborg, where he is a senior wireless network specialist. His current work is related to radio resource management and 3GPP standardization of LTE. He has been appointed as apart-time professor at Aalborg University in the Wireless Communications Networks (WCN) section.

NIELS T. K. JØRGENSEN (nj@es.aau.dk) received his BSE and MSE from Aalborg University, Denmark in 2007 and 2009, respectively. Since 2011 he has been pursuing his Ph.D. degree, also at Aalborg University. His research interest focuses mainly on radio resource management and interference management in heterogeneous networks or small cell networks.

VÍCTOR FERNÁNDEZ-LÓPEZ (vfl@es.aau.dk) received his Master's degree from the University of Granada, Spain, in 2012. He is presently a doctoral student in the Wireless Communications Networks section, Aalborg University, Denmark. His primary research interests are LTE resource management and heterogeneous networks.