INTERFERENCE-AVOIDANCE TECHNIQUES

Improving Ubiquitous User Experience

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his article presents interference-avoidance schemes developed in the Advanced Radio Interface Technologies for [Fourth Generation (4G)] Systems (ARTIST4G) Project for three scenarios targeting the deployment of Third-Generation Partnership Project (3GPP), long-term evolution (LTE)-advanced networks, and beyond. In the first scenario, we propose three-dimensional (3-D) beamforming as a flexible technology for taking the best benefit from the internode cooperation, constrained by the core network infrastructure. The second scenario addresses a long-term deployment with nonconstrained internodes cooperation link based on an interference-shaping strategy that allows for exploiting at its maximum the coordinated multipoint concept. Finally, we investigate interference coordination mechanisms for protecting the macro network from a massive deployment of small cells that provides a network capacity increase by high offloading capabilities.

Introduction

The main paradigm of the 3GPP-LTE network is to build a cellular network in which the core network is not aware of the radio access network. This results in delegating the radio resource management, including users' scheduling and power control, to the enhanced Node B (eNB) base stations. Without any cooperation between eNBs, high interference levels are experienced at the cell edge, resulting in unfairness between cell-center users taking benefit from high data rates transmission schemes, and cell-edge users experiencing low signal to interference plus noise (SINR) levels. Thanks to an X2 logical cooperation channel set up between the eNBs, the cell edge throughput is improved by using intercell interference coordination

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techniques via semistatic power profiles and multiuser scheduling.

The results presented in this article are the output of the work-package 1 of the European ARTIST4G Project (see https://ict-artist4g.eu/), the goal of which is to improve the ubiquity of user experience, or in other words, reduce the gap between the cell edge and cellcenter throughputs. Three main strategies are investigated, they can be exploited altogether: interference avoidance employs transmitter-side techniques, interference cancellation involves the use of advanced receivers; and small cell deployments (relay, pico- or femto-cell) are studied for the sake of coverage extension and offloading.

In this article, we focus on promising innovative interference-avoidance schemes using advanced transmitter signal processing and scheduling, taking into account the architectural constraints of the cellular network deployment. We focus on three main scenarios as illustrated in Figure 1, keeping in mind they can be used all together in the system, according to the user equipment (UE) capabilities and effective deployment.

First, we investigate how the vertical dimension of the 3-D beamforming obtained with down-tilting at the antennas allows for dynamically reducing interference and improving cell edge throughput for macrocellular



FIGURE 1 Illustration of interference-avoidance schemes. (a) 3-D beamforming. (b) Interference shaping. (c) Heterogeneous networks.

networks where the X2 cooperation interface between two neighbors only support the control plane exchange (i.e., channel state and scheduling information).

We then assume a more futuristic deployment where neighboring nodes can cooperate through a low-latency high data rate channel and convey user plane (users' data) traffic. The investigated schemes are based on overlapping coverage areas, partial coordinated multipoint (CoMP) transmission and interference floor shaping. It provides a framework for interference mitigation in various application scenarios. These techniques also make use of down-tilt adaptation and therefore can benefit from the 3-D beamforming technology.

Finally, we consider the use of a dense network of small cells like home base stations (HeNBs), with high frequency reuse as a crucial step toward higher throughput and user fairness. Therefore, advanced interference-avoidance techniques have been developed specifically for this heterogeneous deployment and are applied in combination with optimized resource allocation schemes. A new architectural node is required and defined in order to enable the cooperation between the high number of small cells and the eNBs, allowing for the clustering of small cells into a reduced number of virtual radio neighbors for the eNBs.

Advanced 3-D Beamforming

The beam pattern of an eNB is an important parameter that influences intercell interference in multicell systems. For current practical deployments according to the 3GPP-LTE standard release 8 (LTE release 8), the horizontal antenna pattern is usually fixed and arranged in sectors oriented so as to avoid facing beams between two radio neighbors. On top of this static planning, more dynamic beamforming or MIMO technologies among the antenna elements of the cell are applied in order to have a spatial control of the interference on the horizontal plane.

Exploiting Advanced 3-D Beamforming at the Scheduler Level

The vertical antenna pattern or down-tilt is also an essential parameter for performance optimization, and remains usually fixed in conventional systems. We take benefit of a signal processing that enables dynamic beam steering also in vertical direction, so as to serve each UE with an individual down-tilt. To restrict inter-cell interference in a multicell environment, the down-tilt serving UEs at cell edge is limited to a certain minimum value. The UE-individual down-tilt can be applied either in each cell independently [5], [11], only depending on the location of the UE, or in combination with coordinated scheduling of the beams of adjacent eNBs.

The first approach already provides a significant statistical reduction of the interference at cell edge on

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resources allocated to UEs closer to the eNB [11], without requiring any cooperation between the eNBs. Thus it can be used in deployments according to 3GPP-LTE standard releases 8 and 9 without any exchange of information on the down-tilt between the base stations.

The main principle of the second approach is to constrain the schedulers to allocate cell-edge users of one cell on the same resource as the non-cell-edge users of the neighboring cells. In combination with downtilt adaptation, the level of interference caused by UEs closer to the eNBs is being highly reduced. This is illustrated in Figure 1(a), where the different colors correspond to different resources. By considering the red beams, we observe that the cell-edge user scheduled on that resource experiences low interference from the two neighboring eNBs, which serve non-cell-edge users with higher down-tilted beams. The scheduling coordination can be performed on a long-term basis with a mapping of the resources on specific beam down-tilts. This mainly improves the cell edge throughput while maintaining or even increasing the spectral efficiency (SE) [4], [12]. Thus, it can be used in LTE release 8 or 9 deployments, on top of a soft frequency reuse intercell interference coordination (ICIC) scheme [13], which is already supported.

The scheduling constraints can also be exchanged in a more dynamic fashion between neighboring eNBs. To derive these constraints, specific feedback information on adjacent cell interference is assumed to be available. The dynamic vertical beam adaptation capability is used as an additional degree of freedom for the scheduler to dynamically minimize the interference level for each UE and maximize performance while respecting the constraints.

Simulation Results

A simulation study of a multicell scenario (seven sites, three cells each), investigating the cell edge throughput versus the SE under ideal conditions, shows the high potential of 3-D beamforming with beam coordination, compared with the case of conventional fixed down-tilt and the case of only horizontal beam coordination (Figure 2). The intersite distance is 500 m, the eNB height is 32 m and the propagation model is the 3GPP spatial channel model enhanced (SCME) case 1 [1]. Fifteen UEs per cell are randomly distributed and scheduled by a weighted proportional fair scheduler with fairness parameter α [5]. Whereas horizontal beam coordination already shows 6.5% gain in SE and 19% in cell edge throughput,



FIGURE 2 Advanced 3-D beamforming simulation results. The SE versus cell edge throughput, baseline case 1, SCME; 4×1 single user (SU)-mutliple input, multiple output (MIMO); intersite; 3 km/h; parameter 0.3 = number of constraints (max 3 per interferer); 5% ile = 5 percentile, i.e., the value that gives 5% on the CDF.

the introduction of 3-D beamforming gives additional gains of 9.6% in SE and 29.9% in cell edge throughput. This last approach is the most promising in terms of performance, but it requires more control signaling exchange on the cooperation interface, which would be supported only from the 3GPP-LTE standard release 11 or beyond.

Validation of the Concept with Field Trials

The idealized simulation assumptions, i.e. exact channel knowledge, zero delay of information exchange, the



FIGURE 3 CDF of the received power for down-tilts 0°, 3°, 6, ° 9° and calculation of optimum down-tilt for a feedback loop with 1-s delay.

idealized beam pattern, and the vertical channel assumed to have only line-of-sight components as defined by [1], give an overly optimistic view. To assess the relevance of the results in a real environment, additional investigations and field measurements are needed. Therefore, the first field trials have been set up to examine the propagation performance in the downlink direction for different antenna down-tilts to get a proofof-concept for the behavior of the vertical channel. These measurements were conducted in a single-cell scenario and are basically intended to verify the relation of down-tilt angle versus distance from the base station, even in a non-line-of-sight environment.

Figure 3 shows the results of the field trial with an antenna array equipped with four single columns that can be tilted separately. The aperture of the vertical pattern of the antenna columns was 6.2° at 2.6 GHz, and the distance between the antenna columns was 26 cm. Each single antenna element was fed with signals with dedicated and distinguishable pilots from an eNodeB emulator. This arrangement allowed us to simultaneously measure up to four data streams transmitted with different down-tilts with a dedicated radio network analyzer during drive tests. Baseline measurements with a down-tilt of 6° for all four antenna elements have been done for different drive routes in the test bed. The drive

routes have been chosen in such a way that it could be clearly distinguished between regions with mostly line of sight conditions and regions with strong fading conditions. Test drives were done for different settings of the down-tilts of the antenna array. The down-tilts of the antennas have been varied between 0° and 18° with a step size of 3°. The first observation was that fast fading effects hide the impact of different down-tilts to the received signal at the terminal device. Therefore, the raw data are integrated over adequate time intervals to neglect the fast fading effects. As can be seen in Figure 2, small tilts lead to improved receive signal strength at the cell edge, corresponding to low receive (Rx) SNR, and high tilts improve the signal strength more in the center of the cell, corresponding to high Rx SNR values. At medium Rx SNR values (20-30 dB SNR), the cumulative density function (CDF) curves therefore show characteristic intersections. We observed a slow change of the optimum down-tilt for drive test with velocities of up to 20-30 km/h. The variation of the received-signal SNR due to down-tilt variations was up to 15 dB, which gives a high potential for a significant throughput gain. Downtilts larger than 10° did not show big advantages.

In the next step, beamforming field trials with adaptive antenna arrays in a single-cell scenario with one or more UEs have been conducted [15] to test newly developed algorithms for beam pattern adaptation in realistic environment and to evaluate the impact of different algorithms to the performance metric. These results are used to refine the system simulation assumptions. Therefore, simulations and field trials need to go hand in hand and feature reliable system-level simulations that are verified by field trials to prove the practicality of proposed innovations.

Advanced Interference Mitigation

To further improve the cell edge and average throughput, we consider potentially complex but powerful midto long-term solutions for interference mitigation. From the 3GPP CoMP study [3], it is well known that joint precoding solutions including intra- and intersite cooperation often only provide moderate performance gains, even under ideal conditions. In a first thorough analysis, main shortcomings of more simple CoMP schemes were identified, like the inflexible setup of cooperation areas (CA) leading to a low percentage of beneficial UEs, limited CoMP gains for cell-edge users (UE) due to a strong interference floor, and degradations related to outdating or quantization of the channel state information (CSI).

We consider a new deployment illustrated in Figure 1(b), where no limitations on the cooperation interface exist, i.e., control and data plane can be exchanged without data rate or latency constraints. Thus, this scenario is foreseen for future deployments, such as deploying a new network in a dense urban environment.

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Overlapping Cooperation Areas and Cover Shift Setup Forming joint processing (JP) CoMP CAs is the first step strengthened by two observations: backhauling should be limited to neighboring sites and investigations in [5] indicate a strong performance gap for distributed compared to joint precoding.

We consider comparably large CAs spanning over three sites (or, equivalently, nine cells in the case of three sectors per site), which significantly increases the amount of UEs observing several strong cells at the same time from one of the predefined CAs.

The network is then paved with a seamless allocation of such cooperation areas. In order to provide a new degree of freedom, overlapping CAs are being defined with a different setup of CAs on orthogonal resources like frequency sub-bands, called cover shifts (see Figure 4). The cover shift and CA define the scheduling domain for each UE, and are selected in order to maximize the number of strongest cells in the CA and minimize the number of interferers from other CAs.

Interference Floor Shaping

The intra-CA over inter-CA signal ratio can be further improved by a novel interference floor shaping technique illustrated in Figure 1(b), relying on wideband (WB) beamforming, cover shift-dependent antenna tilting and Tx- power allocation. The transmit power allocation and vertical beam tilting are optimized semistatically per CA and cover shift, minimizing



FIGURE 4 Exemplary two cover shifts in two different frequency bands allowing scheduling UEs into the CA centers.

out-of-CA interference power leakage while satisfying CA center coverage constraints [6].

User Grouping

Another key technology with respect to JP CoMP is to find an optimum mutual orthogonality maximizing user grouping, being a real challenge in the case of enlarged nine-cell CAs and, e.g., 2-4 WB beams per cell. A very effective two stage CoMP scheduler has been developed, relying mainly on a powerful per cell user grouping. Each cell transfers its results to the quite simple secondstage per-CA-scheduler, which is responsible for the joint precoding and potentially some fine tuning of the per cell scheduling decisions. This two stage approach has been motivated as to overcome the potentially strong correlation between WB beams of single cells, being a result of the collocated antenna elements forming the WB beams. Inter site correlation is typically much lower with accordingly lower scheduling restrictions.

Simulation Results

This overall framework takes interference mitigation to a new level and promises significant gains with respect to SE and coverage as indicated by the first ideal system-level simulations. For comparison, we take the 3GPP LTE release 10 4×4 multiuser multiple input, multiple output (MU-MIMO) and JP-CoMP results as being reported in [2], being the outcome of the CoMP study item for typical urban macro case 1 scenarios with intersite distances of 500 m. Table 1 provides (when available) the performance contributions as can be expected from the different parts of the framework, either in the form of the achievable average and cell edge SINR or as the overall SE. The latter is calculated taking the typical LTE overhead for synchronization, guard bands, and control channel into account. We also provide the gross SE obtained by ignoring any overhead for network-wide CoMP and the proposed framework. A gain of 240% is obtained by the proposed concept, which is a significant step toward achieving ubiquitous user experience [16] and approaches the theoretical network-wide CoMP performance. Keeping as much as possible of these gains for realistic channel estimation and reporting schemes is the next challenge we are addressing.

Channel Prediction Enables JP CoMP

Any CoMP transmission requires the cooperating base stations to acquire the downlink CSI in order to enable MIMO-like joint precoding at the transmitters. In practice, the CSI will be imperfectly acquired and shared across the transmitters, making it desirable to develop robust precoding methods which are tailored to the multicell MIMO scenario. Initial research on such methods has been reported in [5], [14]. When the backhaul cooperation channel is limited, some techniques such as partial joint precoding can be adopted. Furthermore, channel estimation and effective feedback schemes are seen as essential main enablers, and a parameterized feed back compression and channel prediction scheme have been designed. The main idea is that UEs feed back accurate location information to the eNB. The eNB reconstructs the wideband radio channels for all required channel components based on an accurate knowledge of the surrounding propagation environment. Simulation results for state-of-the-art Wiener or Kalman filtering indicate that

 TABLE 1
 SINR and SE of different CoMP schemes with respect to an LTE release 10

 4x4 MU-MIMO scheme as reference.

	SINR [dB]			
	cell edge	average	SE bits/s/Hz/cell	SE gain [%]
Network-wide CoMP ⁽¹⁾	-	-	8/15 ⁽²⁾	160
Network-wide CoMP with nonlinear precoding ⁽¹⁾	-	-	11/20	250
3GPP MU-MIMO	-	-	3.1	0 (reference)
3GPP JP-CoMP	-	-	4.0	30
9-cell CoMP ⁽³⁾	-2	12	-	-
+ cover shift ⁽³⁾	4	17	-	-
+ IF floor shaping ⁽³⁾	12	23	-	-
+ 2-stage scheduler ⁽⁴⁾	5	22	7.5/13 ⁽²⁾	140

(1) Simulation conditions are not fully comparable; higher values are for nonlinear precoding

(2) Values after backslash ignore LTE overhead of 43%;

(3) SINR for single UE per cell and for 4x2;

(4) SINR for 3 out of 10 simultaneously scheduled UEs per cell and 4x4 configuration

even for our most advanced interference mitigation framework CSI prediction with sufficiently high accuracy is possible, at least for low to very low speeds. At the same time, further improvements in this area are highly welcome to minimize the performance gap with respect to ideal channel estimation. The natural next step will be to combine state-of-the-art Wiener with parameterized channel prediction.

Interference Avoidance for Heterogeneous Deployments

The deployment of small cells (relays, pico- or femtocells) is an efficient solution for increasing the network capacity by providing a huge offloading capability, i.e., serving as many UEs as possible with neighboring low-loaded cells. Thus, the use of a dense network of small cells with high frequency reuse is a crucial step toward high throughput and user fairness. Unfortunately, the cost of the operation and maintenance of small-scale operated cellular networks is high, and it is difficult to answer to stringent seamless mobility requirements. Considering heterogeneity of nodes for providing the best quality of service to users everywhere is one of the breakthroughs of modern cellular networks. This includes the use of a macro (eNB) cellular network layer, used as a background service and mobility provisioning, supported by relays, picocells or femtocells (HeNBs), with a coverage of tens of meters and used as gap fillers or offloading cells in dense urban scenarios. The difference between these types of nodes is mainly the physical and logical channels they use to communicate with the core network. Relay nodes use a wireless backhaul to a donor eNB, picocells are deployed by the operator while HeNBs are deployed by the customers and use their fixed internet access. Furthermore, a closed subscribed group (CSG) limits the access to a HeNB to a very limited subset of UEs, usually belonging to the HeNB's owner.

Protecting the Downlink of the eNB Network from HeNBs

In this section, we focus on the deployment of femtocells inside homes, called HeNBs in the 3GPP LTE

terminology. A HeNB network is in essence random in space and time, and because of the high number of deployed nodes, it is a potential threat in terms of interference for the macrocellular network. Indeed, the CSG disables the hand-over from an eNB-UE to a neighboring HeNB, which creates a coverage hole in the downlink of the eNB network for each HeNB using the same resource as the eNB. However, a cochannel deployment of HeNBs and eNBs is a fantastic offloading potential we cannot ignore, and the keys of success of the HeNB deployments are coexistence techniques and architecture solutions.

The specific architecture of HeNB networks does not allow fast cooperation between eNBs and HeNBs through the core network for the current LTE releases. Thus, blind or low-cooperation interference-avoidance schemes must be targeted. For UE connected to the macro network (macro-UEs) close **C**ONSIDERING HETEROGENEITY OF NODES FOR PROVIDING THE BEST QUALITY OF SERVICE TO USERS EVERYWHERE IS ONE OF THE BREAKTHROUGHS OF MODERN CELLULAR NETWORKS.

to the HeNB building, power setting is an efficient way to reduce inter-cell interference. In downlink, the HeNB interference is geographically limited, but depends on the HeNB position in the cell. This is illustrated in Figure 1(c), where the coverage area varies for a constant power setting approach (no eNB/HeNB ICIC), whereas we have proposed a blind power setting strategy for HeNBs, relying only on measurements at the HeNB, that provides a control of the coverage hole generated by an HeNB on the eNB network. When compared with fixed power setting in Figure 5 (see [6] and [9] for more details), our blind power setting allows for achieving an excellent tradeoff between the cell edge throughputs observed at the eNB and HeNB networks, even for extremely high densities of HeNBs (500 HeNBs/km²).

Improved performance can be achieved with a higher degree of cooperation, for example, with a coordinated eNB beam selection [6], [8] and with subframe muting, for the sake of orthogonalizing the eNB and HeNB signals



FIGURE 5 Tradeoff between the eNB cell edge throughput and the HeNB network cell edge throughput with and without the proposed power setting strategy and for different HeNB deployment densities.

IN TERMS OF ARCHITECTURE, THE MOST LIMITING ASPECT FOR ENABLING AN ENB/SCS COOPERATION IS THE NUMBER OF RADIO NEIGHBORS OF A NODE.

in the time domain, as illustrated in Figure 1(c), which also solves the problem of eNB-UEs located inside the coverage of an HeNB.

Protecting the Uplink of the eNB Network from Small-Cells UEs

We now focus on the deployment of any kind of small cell (SC) under the coverage and the same resources as an eNB. In the uplink, each SC-UE has a small impact on the macro network, but the high number of SC-UEs multiplies the level of interference. This can be controlled at each SC via a power control function, parameters are obtained from a long-term cooperation between the SCs and the macro network. We have proposed in [6], [10] a power control strategy that achieves a good tradeoff between the eNB and SCs cell edge throughput, while also achieving a good power consumption for the SC-UEs. This is based on a first step of measurements in the downlink by the SC-UEs and eNB UEs, and it requires a central entity that gathers measurements in a second step from the SCs and the eNB and deduces the parameters set for the power control function. This set is broadcasted in a third step to each SC, which deduces in a fourth state its power control strategy from its downlink measurements on the eNB and the parameter set. The four-step approach is shown in Figure 6.

Small Cell Grouping, an Architecture Enablers for Interference-Avoidance Solutions

In terms of architecture, the most limiting aspect for enabling an eNB/SCs cooperation is the number of radio



FIGURE 6 Uplink power control scheme for eNB protection in heterogeneous networks.

neighbors of a node. Indeed, an eNB has potentially hundreds of small cells deployed under its coverage, each one being a new radio neighbor. For full cooperation capabilities, each eNB must set up and maintain as many X2 cooperation interfaces as the number of radio neighbors, which is limited to around ten radio neighbors for complexity reasons. An architecture solution has been proposed in [7], where we have investigated the role of an SC gateway to cluster the SCs from the eNB perspective.

We have also introduced [7] a concept for supporting the SC/eNB cooperation as early as possible in future LTE deployments. We propose to virtually make the SC deployment appear as a unique radio neighbor to the eNB. From the radio access point of view, the eNB must be able to make measurements on the SC deployment as if it were a single node. Thus, we have proposed that each SC broadcasts a group physical cell identity (GPCI) at the same time as its own physical cell identity, usually used for radio neighboring node identification. As a result, when the eNB gathers measurements on the virtual cell signaled by the GPCI, the whole SC deployment appears as a single cell, spread in space. The SC-Gateway plays the role of network interface to the SC deployment, setting up and exchanging cooperation messages with the eNB. Thus, the number of radio neighbors of each node is kept reasonable, and the proposed interference-avoidance schemes support such a clustering of SCs.

The above-mentioned power setting strategies for eNB/SC ICIC [6], [10] are architecture-aware solutions, designed under the SC clustering assumption, and they have proven very efficient even under the limited signaling assumption.

Conclusions

In this article, we have shown the main outcomes of the Work-Package 1 in the ARTIST4G Project in terms of interference avoidance. We have shown our strategy to integrate various technologies to meet the requirements of complexity, backward compatibility, and architecture for three identified scenarios. For short-to medium-term deployments of the LTE release 10, we have illustrated how the 3-D beamforming gives additional degrees of freedom, which can be exploited through cooperation to improve the user experience ubiquity. For future deployments of macro cellular networks, when the core network infrastructure does not limit the cooperation between the eNBs, we have shown a combination of principles that maximizes the gain provided by CoMP transmissions. Finally, we anticipate the success of HeNB and SC deployments by providing architecture solutions and architecture-aware interference-avoidance schemes for protecting the macro cellular network. The next step is to extend the scope of these studies to

heterogeneous networks also including picostations and relay nodes.

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