THE ROLE OF SMALL CELLS, COORDINATED MULTI-POINT AND MASSIVE MIMO IN 5G

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Abstract: 5G will have to support a multitude of new applications with higher peak and user data rates, reduced latency, enhanced indoor coverage and additional requirements. This will be achieved by more flexible and larger spectrum usage. In the focus of this paper are advanced techniques for higher spectral efficiency and optimized cell edge user coverage. The first pillar is a powerful interference mitigation framework based on joint transmission coordinated multipoint (JT CoMP). JT CoMP is currently in the phase of transition from theoretical to practical concepts, with the aim of retrieving significant parts of the theoretical performance gains also considering real world impairments. JT CoMP is a complex and sensitive solution that needs a careful system design. We highlight the main means for success like efficient clustering and user selection, interference-floor shaping, scheduling, channel estimation and prediction. A second step is the smooth inclusion of small cells into macro-cellular mobile networks being indispensable for the expected traffic growth in ten or more years from now. Massive MIMO is the third important research topic promising extremely high spectral efficiencies due to strong beam-forming gains. The challenge is to find a smart combination of all these techniques exploiting synergies and keeping the overall complexity acceptable.

1. Introduction

From the data traffic evolution of the last years, high capacity demands can be expected for the future evolution of mobile radio. Around the year 2020, a new fifth generation (5G) of mobile networks will have to deliver probably up to 1.000 times more traffic to mobile users compared to 3GPP LTE Release 8. Due to long evolution cycles in the wireless industry, research has to be conducted now for assessing the most promising techniques able to meet the challenging targets at reasonable costs [1].

A combination of more cells – so called small cells -, more spectrum being used more flexibly together with a higher spectral efficiency seems to be a reasonable break-down of the factor of 1.000 into manageable sub-terms, where the focus will be on small-cell enhanced macro-cell networks, sometimes termed HetNets.

Our reference cases are 3GPP LTE Release 8 to 11, which are highly sophisticated systems comprising the results of a vast amount of research over many years. Spectral efficiencies are now in the range of 2-3 bit/s/Hz/cell. Outperforming the well-designed LTE system by a factor of ten, i.e. 20 bit/s/Hz, constitutes a true challenge.

From a high-level point-of-view, there are three main contributors to higher spectral efficiency, i) advanced interference mitigation concepts, ii) small cells for densification of the network deployment and iii) massive MIMO, i.e. a significant increase in the number of antennas at the evolved base station (eNB) and potentially at the user equipment (UE) as well.

Advanced Interference Mitigation

Inter cell interference is a known challenge from the beginning of mobile radio. In 2G mobile radio systems, simple frequency-reuse schemes proved to be powerful. However, from theory it is well known that higher spectral efficiency requires all cells to be active in the whole spectrum at all times. In LTE, more sophisticated coordination schemes like inter-cell interference coordination (ICIC), enhanced eICIC or further enhanced FeICIC coordination have been introduced. As the names state, these coordination schemes do not really eliminate inter-cell interference. Therefore, gains are limited to medium load conditions.

Comparing the performance of a single, isolated cell with that of an active cellular network, a significant performance gap is still observed. For interference-limited scenarios, theoretical gains of 300% and more have been promised for full network-wide JT CoMP [2], which eliminates the inter-cell interference. These results have motivated 3GPP to complete several CoMP study and work items. But achieving CoMP gains at system level in reality – even for ideal channel knowledge - turned out to be difficult.

There are principal limitations due to impairments, such as synchronization and delayed feedback. Moreover, there are man-made limitations concerning clustering, user selection and feedback. Our analysis lead to a more advanced interference mitigation framework denoted as IMF-A [3]. Beside JT CoMP, it includes new approaches for clustering, user grouping, interference-floor shaping, feedback compression, channel prediction and scheduling. In this way, performance gains in the order of 50 to 100% or even more are found feasible when taking practical constraints into account.

Small Cells

The interference mitigation framework described above has been designed for macro-cell networks. A main task at present is to integrate large numbers of small cells into this framework. For advanced techniques like JT CoMP, small cells have specific characteristics. They are placed as add-ons into the macro-cell, have lower Tx power, potentially no direct backhaul link to the macro-eNB and different radio propagation characteristics, e.g. due to below-rooftop deployment.

An intuitive solution followed in 3GPP is to setup different and independent frequency layers for small and macro cells. While this solution is very robust, and enables parallel macro- plus small-cell transmission in all available frequency bands, it sacrifices spectral efficiency. Future research will have to assess if full reuse can be made more economic taking the extra complexity into account.

Massive MIMO

The outcome of this assessment might depend on a third technique, the so-called massive MIMO [4]. This term has been introduced for having much – e.g. ten times - more antennas at eNBs available as compared to the total number of receiving antennas among the served UEs. In this way, significant beam-forming gains are possible at each terminal. For large numbers of antennas, however, the so called pilot contamination sets an upper bound to the performance. For a 5G system, it is also important to note that antennas are not for free in terms of complexity and cost, i.e. they should be added only to the extent that substantial system gains are possible. For these reasons, we propose an enhanced version of the IMF-A framework, combining it with small cells as capacity boosters and massive MIMO - or rather enlarged MIMO – to make the system more robust and to increase the number of users.

One can take another perspective at integrating small cells and massive MIMO into the interference mitigation framework. Currently, base stations broadcast the signal power intended for a single terminal over large areas. With massive MIMO, the mobile network is turned into a more focused and energy-saving system, directing the power to those locations where it is needed while interference to users in other cells is minimized. In the same context, small cells deploy transmit points closer to the users, thereby reducing the path-loss and increasing the line-of-sight (LOS) probability. JT CoMP - being essentially a distributed MIMO system - provides macro-diversity and controls the residual inter-cell interference.

2. Advanced interference mitigation – current status of CoMP

JT CoMP is able to convert an interference-limited mobile radio network into one that exploits the potential interference for data transmission. In theory, this works very well. For network-wide cooperation assuming ideal channel knowledge, two to three times higher spectral efficiencies have been predicted [2]. In reality, however, there are several limitations and impairments making JT CoMP a challenging technology. Fundamental requirements are proper synchronization between cooperating cells and sites, ensured by GPS or the IEEE 1588 precision time protocol. JT CoMP requires fast exchange of user data between all cooperating cells, which is best achieved using fibre backbone networks. JT CoMP can be implemented either in a central unit for all cooperating cells, or the processing is distributed among the sites. Real-world multi-site demo systems e.g. at the Fraunhofer HHI in Berlin and the Technical University in Dresden validated that all physical layer (PHY) functions of JT CoMP can be handled with some extra effort [5]. From our point of view, enhanced higher-layer functionality is now more important. This includes sophisticated solutions for user-centric clustering, interference-floor shaping, user selection, accurate channel estimation, robust precoding based on advanced channel prediction - simultaneously limiting the reporting overhead for the channel state information (CSI) - and a frequency-selective scheduler. In the following, we describe recent findings concerning these research topics.

Clustering

It is well accepted that cooperation has to be limited to few cells or sites as otherwise the backbone traffic for the exchange of user plane data, the number of pilots and the feedback overhead for CSI reporting of all channel components (CC) will explode. Measurements in real networks indicate that interference can be strongly limited to a variable but rather small number of cells by using the antenna down-tilt. This feature enables us to form clusters in the network denoted as cooperation areas (CA). CAs should include the strongest interferers for all jointly served terminals. Simultaneously, they should enable a high percentage (ideally 100%) of users to gain from cooperation.

While network-wide cooperation would completely eliminate the interference, a clustered network leads inherently to residual inter-cluster interference. It has been identified already in early research that clustering and user selection is an NP-hard problem, where the optimum among a very large number of possible cluster configurations is searched [6]. Fortunately, an efficient heuristics is meanwhile available to overcome this issue.

This set of techniques consists of two components that work on different time-scales. On a longer timescale, a static clustering approach is used to reduce the overall interference. In a first step, the CA is enlarged to e.g. nine cells by cooperation over three adjacent sites with three sectors per site. Three sites are used for practical reasons as they require only two inter-site links. Enlarged cooperation areas increase the probability that users have at least their three strongest interfering cells inside the CA. But still, there would be many users at the edge of the CA being interfered by two adjacent CAs. Out-of-cluster interference is the main reason for reduced performance even in case of relatively large CAs. For that reason, we introduced overlapping CAs - so called cover-shifts - on different frequency sub-bands or time-slots. A CA edge user can then be scheduled into another cover-shift, where the user is in the centre of the corresponding CA. The cover-shift concept can be supported by active antennas having variable down-tilts. A small tilt is then used for CA inbound and a strong tilt for outbound beams. Together with suitable power allocation, the interference floor can thereby be suppressed to less than -20dB [7].

A second step is applied on a shorter time scale. The cover-shift concept still assumes CA-wide cooperation. But it is well known, see e.g. [8], that the performance can be significantly reduced by using a flexible, user-centric clustering where clusters are assembled from the most relevant interferes beside the serving cell according to the individual interference conditions at the UE. Recently, we extended the flexible clustering concept by an iterative successive user grouping approach. To avoid extensive CSI reporting, which is the result of the classical approach searching for orthogonal channel vectors [9], a first user is selected – typically at cell edge – and grouped together with one or more random users from other cells in the cluster. If all cooperating users experience performance gains, the user group is kept. Otherwise, users with reduced performance are replaced by other users randomly selected again. Interestingly, in more than 80% of cases, all the users profit from cooperation already in a very first random trial (Fig. 1 left, US-III). In this way, suitable user groups can be formed after a few iterations only, yielding clusters in which all users gain from cooperation. This approach increases the clustering success rate and thereby the performance significantly (Fig. 1 left, US-IV). In combination with rank adaptation in each cell and frequency-selective scheduling, the performance achieves a well-known bound for cluster-based cooperation (Fig. 1, right, US-IV), where the data rate is limited by out-of-cluster interference only. By forming clusters in a new way, the cluster size and thereby, overheads due to pilots, feedback and backhaul as well as the complexity of joint processing for JT CoMP can be minimized [10].

Sophisticated, flexible clustering and efficient user grouping are the most important means to achieve high JT CoMP performance gains. With the above proposed heuristics, the performance gap to network-wide cooperation can be significantly reduced.

3. Feedback Compression and Channel Prediction

According to Fig. 1, for a 2x2 MIMO LTE system with 500 m inter-site distance, a spectral efficiency of 6 to 7 bit/s/Hz/cell in small cells and of 4-5 bit/s/Hz/cell in macro-cells could be achieved on average assuming ideal channel knowledge at the central unit of the CA. This is more than 100% gain over conventional multiuser MIMO yielding less than 3 bit/s/Hz/cell. Note that “classical” in Fig. 1 refers to single-user MIMO. In reality, however, JT CoMP is extremely sensitive to channel estimation errors due to quantization and channel state information (CSI) outdating for moving terminals. In the following, we consider the potentials of both, compressing the CSI feedback adaptively with controlled performance degradation and compensating the impact of the feedback delay by means of advanced channel prediction.

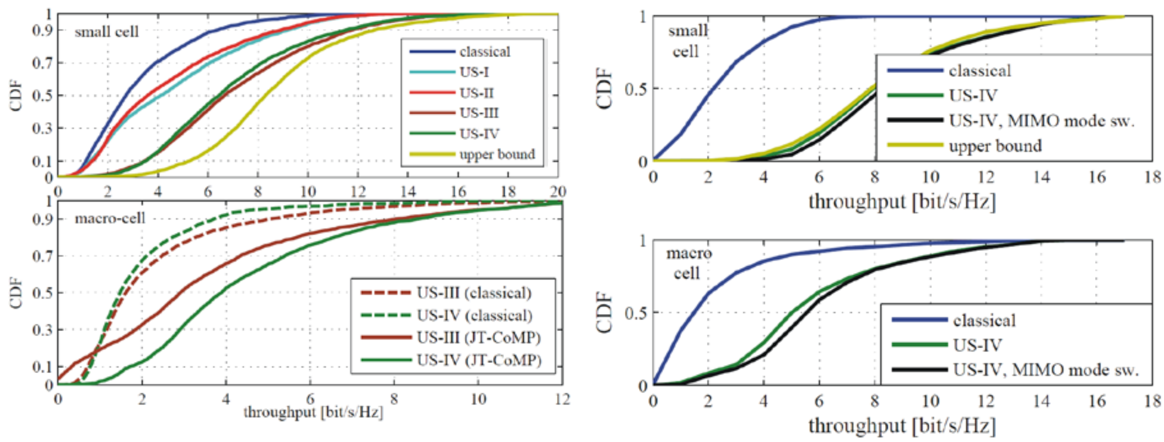

Fig. 1 Left: User throughput in a small cell and in surrounding macro-cells. Right: Optimized performance after rank adaptation and frequency-selective scheduling.

Adaptive feedback compression

The overhead due to the feedback of CSI for JT CoMP is often considered large. The cover-shift concept already limits the feedback to a fraction of the overall bandwidth. Flexible clustering and successive user selection lead to a situation where the feedback requested from the users in order to form a cluster efficiently is already minimized. Besides forming smaller clusters, there is further potential. Going from the frequency-domain, where the pilots are defined, to the time domain, only the most relevant multi-paths can be selected by estimating the noise and out-of-cluster interference floor. The required quantization depends on this floor as well. Hence a combination of flexible clustering, adaptive tap selection and adaptive quantization is useful to compress the feedback.

We evaluated the combined potential of these approaches. Starting from static feedback where a UE provides full CSI from its nearest 7 cells with 16 bit per real- and imaginary value, flexible clustering yields more than a factor of 2 feedback reduction, according to the average cluster size being between 2.5 to 3.5 in our field measurements. Only 22 taps are selected on average, while 144 pilots are dispersed in the frequency domain, yielding a reduction by factor 6. Adaptive quantization leads to further reduction by a factor 2. These effects are not always multiplicative. Altogether, CSI feedback can be reduced by factor 15 on average. We demonstrated also that adaptive feedback compression is implementable in real-time [11].

The performance depends also on the estimation quality of the CSI. It can be impaired by reference signals (RS) reused elsewhere. If we combine the interference-floor shaping method mentioned above and use 40 CSI RS from LTE Release 10 with suitable muting patterns, 20 dB SINR is achievable for 80% of the RS using an overall pilot overhead of less than 10%.

Channel prediction

State-of-the-art prediction techniques like Kalman and Wiener filtering make the JT CoMP system more robust. For CSI delays of few ms and moderate mobility, minor degradations are observed. For robust operation, it is also important to adapt the precoder at the central unit to different reliabilities of the predicted channels [12]. Fortunately, Kalman filters provide such information intrinsically, which can be reported semi-statically from the UEs [13].

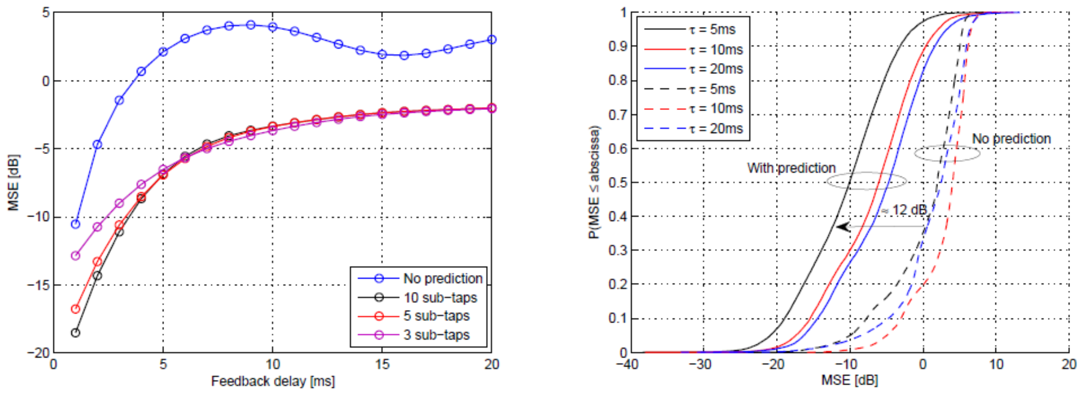

Fig. 2 Left: Average precision of the CSI versus the feedback delay with and without prediction, assuming perfect CSI at the terminal at 30 km/h. The oscillation with no prediction is due to the temporal correlation in the SCME channel. Right: For typical values of the delay, CSI precision can be increased.

Doppler-delay based prediction is a non-linear approach. The channel for each link between a transmitter and a receiver antenna can be modelled by a number of multi-paths with their individual complex amplitude, delay and Doppler shift. From the recent channel history, these parameters can be estimated for each path. Next, we assume that the multi-paths parameters remain static over short periods of time. Then we are able to predict the channel into the future by inserting the estimated parameters into the channel model. This approach has been studied using the standard SCME channel model. Exemplary results in Fig. 2 illustrate that significant improvements can be achieved even for 30 km/h at 2.6 GHz [14].

Channel prediction is similar to weather forecasts: Often it is fine, while sometimes it fails. If prediction is performed at the UE, it can be compared with latest measurements. The UE could inform the central unit about situations with abnormally high prediction error levels via a low-rate low-latency feedback channel.

Any improvement of the CSI translates directly into a performance gains. The achievable SINR due to residual inter-user interference is inversely proportional to the mean square error of the channel estimation. Note that there is an additional impact of the channel matrix in the cluster (see [14] and references therein). Advanced channel prediction is regarded as an important enabler for JT CoMP. A powerful predictor reduces the overhead and counteracts the feedback delay accumulated over the air and while being transported over the backhaul. Ultimately, it allows for significantly higher mobility.

4. Evolution to 5G – small cells and massive MIMO

An alternative way to control interference in cellular networks is by using more base station antennas than spatial streams, also denoted massive MIMO. Asymptotically, the beam-forming gains are so large that residual inter cell - respectively inter stream - interference is low and the spectral efficiency reaches high values, like 100bit/s/Hz/cell or more [4]. Theoretically, the main limitation is the so-called pilot contamination, i.e. the degradation of the channel estimation for increasingly higher number of antennas due to limited reference signals. Solutions exist, for example by exploiting the varying path loss and correlation properties of channels estimated from antennas placed at different sites. In this way, a linear increase of the spectral efficiency versus the number of antennas becomes viable.

In practice, more antennas need extra RF chains, analogue to digital converters (ADC, DAC), and signal processing, which are not for free. Therefore, we propose to combine the idea of massive MIMO with the interference mitigation framework as laid out above and to increase the number of antenna elements per cooperation area gradually so that the effort for a required performance target is minimized.

Deployment options

Different deployment options are envisioned for more antennas:

a) One could upgrade homogeneous macro cells with larger numbers of antennas, thereby overcoming limitations for indoor users and inter-beam correlations (see below). If the number of served UEs is kept constant - e.g. three UEs per cell - moderate extra spectral efficiency gains are expected due to increased diversity. To exploit the full potential, however, the number of parallel streams has to be increased as long as inter-stream interference is kept low. This is in line with the expected growth of the numbers of users, e.g. due to machine-type communication. There is a trade-off between serving fewer users more robustly and increasing the spectral efficiency by adding more users. In best-case conditions, 15 streams can be served by 16 antennas[1] yielding an upper bound of 40 bit/s/Hz/cell assuming 64-QAM and 43% overhead for guard bands, scheduling, synchronization etc. Spectral efficiencies of 10 to 40 bit/s/Hz/cell correspond to 5 to 20 times higher spectral efficiency compared to a baseline LTE Release 8 2x2 system. Adding more antennas at macro sites is a viable option for a future 5G system. Antenna elements can be very cheap. Extra costs for RF frontends are more relevant and research is needed to combine low-cost massive MIMO antennas with sufficient beam-forming flexibility. Benefits of macro-site massive MIMO are that i) there will be no extra site costs, ii) it supports cell wide – or even inter-cell - load balancing, iii) extra backhaul requirements are small and more signal processing can be done at a single site. The main challenge is the increased dimension of the antenna, which is not well accepted in urban areas. Furthermore, there are mechanical issues like increased wind load.

b) A natural alternative is to place further transmitters with moderate numbers of antennas at typical outdoor small-cell locations. Benefits of small cells are shorter eNB-UE distances and a higher LOS probability. High-speed data coverage is improved and diversity is increased. Anyway, more cells yield higher capacity if the frequencies are reused. Placement of small cells will probably start at hotspots leading to inhomogeneous cell layouts implying also a more complex network planning.

c) A third approach is to add indoor small cells, or even more powerful enhanced wireless local area networks, to avoid or even to benefit from the strong outdoor to indoor penetration loss, which might be in the order of 10 to 20dB and even more inside large buildings.

Implementation proposal

A major practical challenge is to handle inter-layer interference with limited complexity. One option is the usage of different RF bands for the macro- and small-cell layers. Alternatively, much work has been conducted in 3GPP to develop inter-cell interference coordination (ICIC), enhanced ICIC (eICIC) and further enhanced ICIC (FeICIC), which are interlayer coordination schemes in the time or frequency domains. Theoretically, full access of macro-

[1] At least one spatial degree of freedom per cell should be kept for diversity

as well as small cells to all frequency bands would be optimal, which is feasible using JT CoMP.

Our envisioned 5G system concept is illustrated in Fig. 3. It includes all three deployment options, i.e. massive MIMO, small cells and enhanced local area networks serving hotspot and indoor areas with high user densities. Together with the IMF-A interference mitigation framework, the macro-cell performance is boosted. A so-called opportunistic CoMP scheduler is connected to all three sites and to the distributed small cells controlling the cooperation of macro- and outdoor small cells.

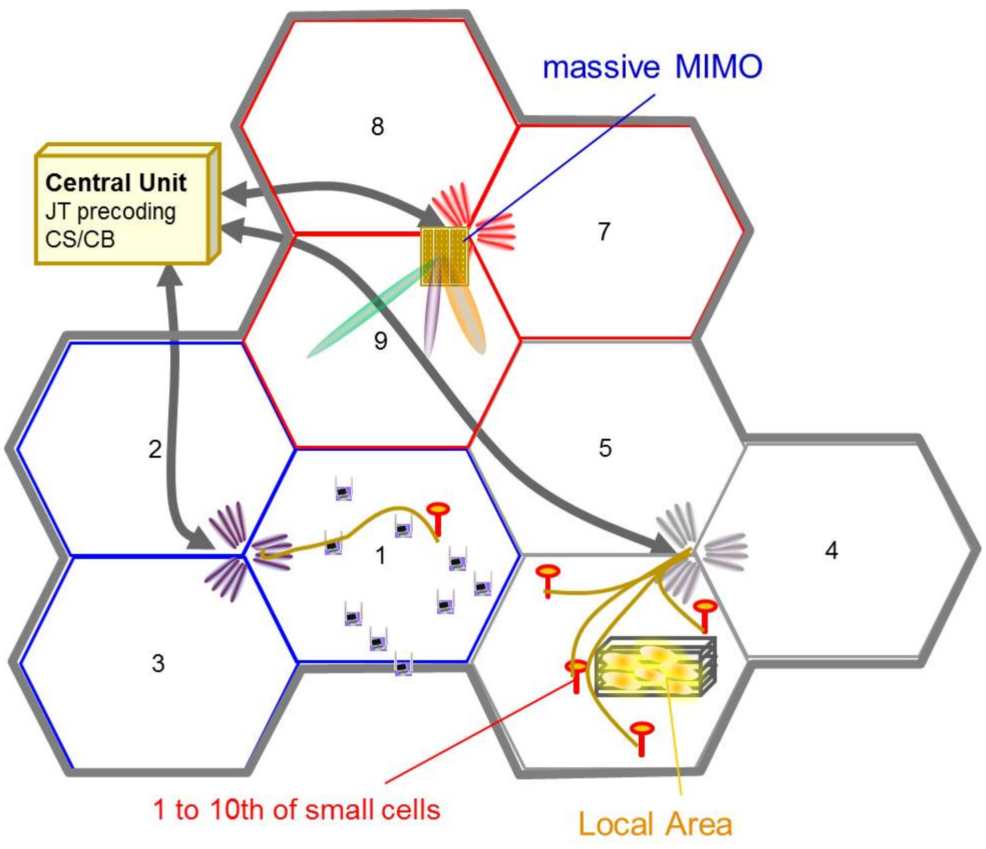

Figure 3: 5G system concept enhancing 4G systems by adding small cells, massive MIMO and JT CoMP for interference mitigation. Interference floor shaping is assumed to overcome inter-CA interference.

Initial results

As already shown in Fig.1, the performance of the proposed scheme is limited mostly by out-of-cluster interference indicating the large potential for JT CoMP for interference coordination in HetNets including macro- and small cells, refer to [11]. Results using the same algorithms also for JT CoMP between macro-cells are provided in [15].

Enhanced robustness

By adding more distributed transmitters (small cells) or co-located antenna elements (massive MIMO), the most important limitations found so far for the IMF-A framework can be overcome. These are the low rank of parallel beams formed by co-located antennas in one cell towards the same direction and SNR limitations for indoor users experiencing strong outdoor-to-indoor penetration loss.

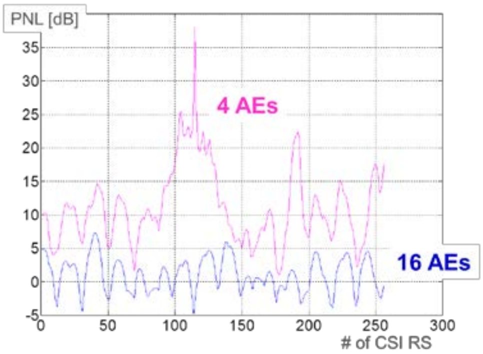

Figure 3: Power normalization loss of ZF precoder serving 3 UEs with 4 and 16 columns of antennas. Each antenna has eight vertical antenna elements, i.e. overall there are 8x16=128 elements.

With a badly conditioned channel matrix, more power is needed to separate the users. Fig. 3 illustrates the resulting power normalization loss as a function of frequency, when zero-forcing linear precoding is used. Results are obtained from ray-tracing simulations for the Munich area near the NSN campus. Three users are served at a distance of less than 50 cm from each other either with a 4- or 16-element uniform linear array over a distance of nearly 250 m. While there are significant losses from 10 to 20 dB with only 4 antenna elements (AE), despite the closely-spaced users, the loss is close to zero dB for 16 antenna elements. Simultaneously, an average array gain of 6 dB is observed. The increased spatial diversity makes the signal processing for JT CoMP more robust in general, e.g. it reduces the impact of prediction errors.

Traffic scaling to reach 5G targets

Finally, we consider the achievable traffic over the air and what traffic will therefore be required in the backhaul. Starting at around 100 Mbit/s per 20 MHz for a 2x2 MIMO LTE site, as a reference, note that the target factor 1.000 in 5G leads eventually to an aggregated over-the-air traffic of 100 Gbit/s per site.

Using recommendations for backhaul estimation from the next generation mobile networks (NGMN) forum, we derived also the backhaul overhead from our measurement-based system-level simulations in a heterogeneous network model (Fig. 4, left) with and without JT CoMP, see [15] and references therein. As a result, the performance can be boosted by a factor of 3 by using JT CoMP, compared to single-user MIMO, if we spend ten times more traffic in the backhaul (Fig. 4, right).

In general, traffic can be scaled multiplicatively by using more spectrum, more antennas, more small cells and JT CoMP on top of all. For example, a 5G operator may reach the targeted factor of 1.000 in 100 MHz spectrum using 10 small cells per sector, 16 antenna elements per cell and JT CoMP.

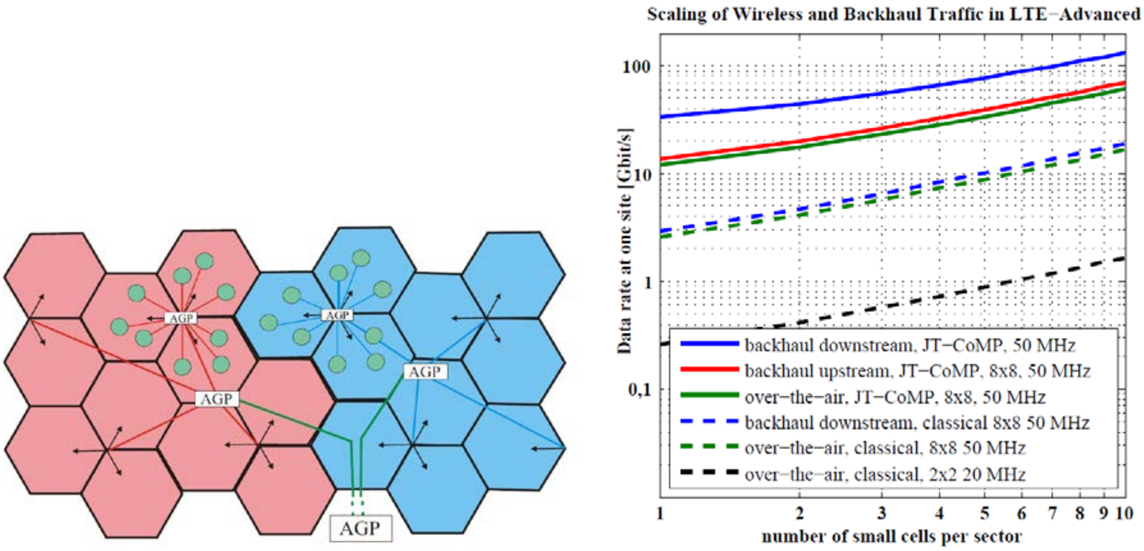

Fig. 4 Left: Model of a heterogeneous mobile network including triple-sectored macro-cells and embedded small cells. Backhaul is organized as a tree using a switch at each aggregation point (AGP). Right: Scaling of mobile data and the corresponding backhaul traffic versus the number of small cells.

5. Conclusions

Our vision of a future 5G system, except for potential additional frequency bands, is a combination of existing and novel technologies like advanced interference mitigation based on JT CoMP, massive MIMO, small cells and enhanced local area networks, to name a few. Compared to a pure massive MIMO scheme, interference mitigation helps to achieve the performance target with considerably less hardware and numbers of small cells at the cost of higher effort in the backhaul infrastructure.

To make our vision happen, several challenges have to be met. Current research is concerned with low-cost low-size and flexibly-usable massive MIMO antennas, accurate channel estimation, powerful feedback compression and prediction, robust precoding for large numbers of wideband beams at macro- and small-cell sites and a low-latency and high-throughput backhaul having low-cost at least for the many small cells. More knowledge about the specific channel conditions with respect to massive MIMO and small cells will be required to assess the performance of this approach more precisely.

Acknowledgements

The authors are grateful to the European Union for funding the collaborative research projects ARTIST4G, METIS and SODALES in its FP7. The German Federal Ministry of Education and Research (BMBF) is acknowledged for support in the collaborative project CONDOR. The German Research Council (DFG) is acknowledged for the project CoMPmobil. The authors would like to thank their colleagues in these projects for the inspiring work atmosphere and specifically, M. Grieger (TU Dresden), M. Lossow, L. Schulz, S. Jaeckel (Fraunhofer HHI), V. Braun (Alcatel-Lucent), C. Oberli, F. Rosas (Pontificia Universidad Católica, Santiago de Chile), W. Mennerich (Nokia Solutions and Networks), R. Apelfröjd and D. Aronsson (Uppsala University) for their invaluable contributions.

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