The Role of Small Cells, Coordinated Multipoint, and Massive MIMO in 5G

Volker Jungnickel, Konstantinos Manolakis, Wolfgang Zirwas, Berthold Panzner, Volker Braun, Moritz Lossow, Mikael Sternad, Rikke Apelfröjd, and Tommy Svensson

ABSTRACT

5G will have to support a multitude of new applications with a wide variety of requirements, including higher peak and user data rates, reduced latency, enhanced indoor coverage, increased number of devices, and so on. The expected traffic growth in 10 or more years from now can be satisfied by the combined use of more spectrum, higher spectral efficiency, and densification of cells. The focus of the present article is on advanced techniques for higher spectral efficiency and improved coverage for cell edge users. We propose a smart combination of small cells, joint transmission coordinated multipoint (JT CoMP), and massive MIMO to enhance the spectral efficiency with affordable complexity. We review recent achievements in the transition from theoretical to practical concepts and note future research directions. We show in measurements with macro-plus-small-cell scenarios that spectral efficiency can be improved by flexible clustering and efficient user selection, and that adaptive feedback compression is beneficial to reduce the overhead significantly. Moreover, we show in measurements that fast feedback reporting combined with advanced channel prediction are able to mitigate the impairment effects of JT CoMP.

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INTRODUCTION

From the data traffic evolution over the last years, high capacity demands can be expected for the future evolution of mobile radio. It is commonly assumed today that around 2020, a new fifth generation (5G) of mobile networks will be deployed. Recent research has identified major challenges such as a massive growth in the number of connected devices and traffic, as well as a wider and more diverse set of requirements and characteristics, starting from low latency and low rate for control messages between devices to multi-gigabits per second for interactive multimedia [1]. Researchers currently investigate how to serve 10 to 100 times more devices, deliver 1000 times the traffic, and to reduce the latency by a factor of 5 for mobile users compared to Long Term Evolution (LTE). In focus are promising techniques to meet these challenges at reasonable costs.

A combination of more spectrum being used more flexibly (i.e., by spectrum sharing), higher spectral efficiency, and additional cells — so-called small cells — seems to be a reasonable breakdown of the main challenge (i.e., 1000 times more traffic) into more manageable subterms. Here, the focus is on small cells embedded into a macrocell network, sometimes referred to as a heterogeneous network (HetNet).

Our reference cases are Third Generation Partnership Project (3GPP) LTE Release 8 to 11, which are highly sophisticated systems comprising the results of a vast amount of research over many years. Reference values of the spectral efficiency are in the range of 2–3 b/s/Hz per macrocell. Outperforming the well designed LTE system by a factor of 10 to achieve 20 b/s/Hz constitutes a true challenge.

From a high-level perspective, there are three main contributors to reaching higher spectral efficiency: advanced interference mitigation, small cells for densification of the network nodes, and massive multiple-input multiple-output (MIMO), that is, a significant increase in the number of antennas at the base station and potentially also at the terminal.

ADVANCED INTERFERENCE MITIGATION

Intercell interference is a well-known challenge from the beginning of mobile radio. In 2G systems, simple frequency reuse schemes proved to be powerful and sufficient. However, it is intuitive that higher spectral efficiency requires all cells to be active in the whole spectrum at all times. In LTE, sophisticated schemes denoted as intercell interference coordination (ICIC) have been introduced. As the name indicates, these schemes coordinate intercell interference but do not eliminate it. Therefore, the gains are limited to small and medium load conditions.

Comparing the spectral efficiency of a single isolated cell with that of a cellular network, a big gap is observed. For interference-limited scenarios, theoretical gains of 300 percent and more have been promised using network-wide base

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station cooperation to eliminate intercell interference [2]. A comprehensive description of practical techniques for joint transmission coordinated multipoint (JT CoMP) can be found, for example, in [5, references therein].

These results have motivated 3GPP to complete several study and work items. But achieving even a fraction of the predicted gains at system level and for real impairments turned out to be difficult. Limitations are caused by delayed feedback and synchronization errors. Further limitations are due to clustering, user selection, and increased overhead.

Performance gains on the order of 50–100 percent were found in [3] taking practical constraints into account. Our analysis in this article leads to a more advanced interference mitigation framework. It includes new approaches for clustering, user grouping, interference-floor shaping, feedback compression, channel prediction and scheduling.

Small Cells

The interference mitigation framework described in [3] has been designed for macrocell networks. It is a new task to integrate a large number 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 macrocell, and have lower transmitter power and different radio propagation characteristics (e.g., due to below-rooftop deployment). Furthermore, they do not always have a direct link to the macro base station enabling coordination on a short timescale.

An intuitive solution is to set up different and independent frequency layers for small and macrocells, or to do time- or frequency-domain ICIC. While this solution is very robust and enables parallel macro-plus-small-cell transmission without interference, it sacrifices spectral efficiency. Our results reported below indicate that full frequency reuse based on JT CoMP enables high spectral efficiency in both small and macrocells, taking the extra complexity into account.

Massive MIMO

The term *massive MIMO* has been introduced for using a much larger number of antennas per site than today. In particular, the number of antennas is assumed to be, say, 10 times larger than the total number of streams served to all terminals in a cell. In this way, significant beamforming gains become possible, and more users can be served in parallel [4].

For large numbers of antennas, however, the so-called pilot contamination sets an upper bound on spectral efficiency. More antennas need more orthogonal pilots for channel estimation. The overhead consumes the radio resources quickly. Nonlinear (i.e., decision-aided) estimators can relax this situation at high signal-to-interference-plus-noise ratio (SINR) where error propagation plays a minor role. Note also that increasing the numbers of antennas is always related to higher complexity and costs; it is intuitive to deploy them gradually. More insights are needed at the system level on how more antennas lead to higher spectral efficiency.

In the following, we propose an enhanced version of the interference mitigation framework developed in [3] in which JT CoMP is combined with small cells and massive — or rather enlarged — MIMO. We review recent achievements in the transition from theoretical to practical concepts and outline synergies when combining these techniques.

Advanced Interference Mitigation: Recent Insights on CoMP

JT CoMP aims at converting a mobile network that is limited by intercell interference into one that exploits the potential interference for data transmission. In reality, however, there are several limitations and impairments making JT CoMP a challenging technology. Fundamental requirements are proper synchronization between cooperating sites, which can be satisfied by GPS or the IEEE 1588 precision time protocol. Either JT CoMP can be implemented in a central unit for all cooperating cells, or the processing is distributed among the sites. While centralized processing requires that sampled waveforms are transmitted from the baseband unit to remote radio heads, in the distributed implementation, fast exchange of user data over the backhaul interconnects between the cooperating cells is needed [5]. Both are best implemented using fiber optics.

Multi-site demo systems (e.g. at the Fraunhofer Heinrich Hertz Institute in Berlin and the Technical University of Dresden) validated that the principal physical layer concept of JT CoMP (i.e., synchronization of distant sites, multi-cell channel estimation, feedback of the channel state information [CSI], synchronous exchange of user data, and joint processing) can be implemented with some extra effort [5]. But there is still room for improvement using more sophisticated algorithms. This includes interference-floor shaping, clustering, and user selection, a frequency-selective scheduler, and more accurate CSI for robust precoding based on predicted channels, simultaneously limiting the reporting overhead. While this was claimed as future research in [5], in the following, we describe our recent progress in these areas.

Clustering and User Selection in Small Cells

It is well accepted that cooperation has to be limited to a few cells because otherwise, the number of pilots, the feedback overhead for the CSI reporting and the backhaul traffic will explode. Several measurements in real networks indicate that interference can be limited to a variable but small number of cells by using the antenna down-tilt. This feature suggests the formation of cell clusters in the network denoted as cooperation areas (CAs). CAs include the strongest interferers for all jointly served terminals. Moreover, a high percentage of the served users are expected 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 in early research that clustering and user selection is a

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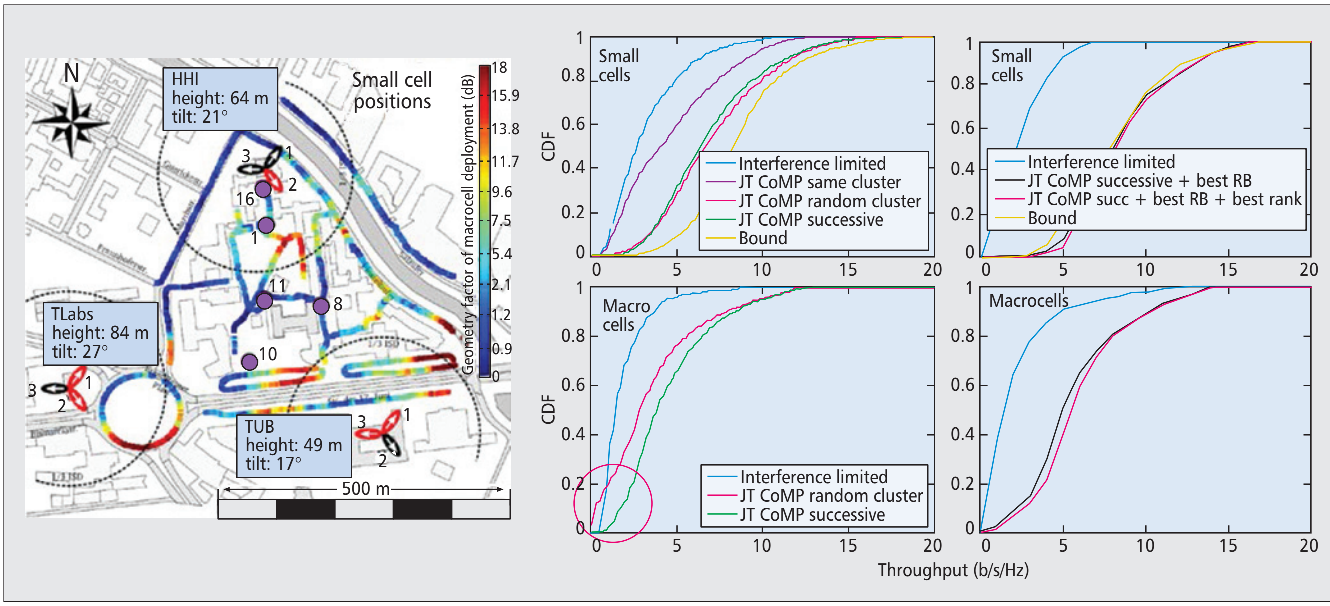

Figure 1. Left: interference-limited macro-plus-small-cell scenario measured in Berlin [10]; center: user throughput statistics for all small cells (top) and all surrounding macrocells (bottom) using the same clustering and user selection and the full rank in each cell over the full 20 MHz bandwidth; right: optimized performance after selecting the 25 percent best resource blocks (RBs) and the best rank in each cell, single- or multi-stream.

NP-hard problem, where the optimum among a very large number of possible cluster configurations is searched. Efficient heuristics are needed for real-time implementation. There are several approaches on different time-scales.

Cover-Shifts — On a longer timescale, a static approach is proposed to reduce overall interference. The CA is enlarged, for example, over three adjacent sites with three sectors per site. In this way, it becomes more likely that users have their strongest interfering cells inside the CA. But still, there are many users at the edge of the CA where out-of-cluster interference is harmful. For that reason, we introduced overlapping CAs, so-called cover-shifts, on different radio resources. A terminal at the CA edge can then be scheduled into another cover-shift, where it is in the center of the CA. The cover-shift concept can be supported by active antennas where a smaller tilt is applied for CA inbound and a stronger tilt for outbound beams. With appropriate power allocation, the interference floor is significantly reduced [6].

On a shorter timescale, flexible clustering and user selection is useful. It is well known [7] that the performance can be improved by using flexible user-centric clustering. Clusters are thereby assembled from the most relevant interferers, beside the serving cell, according to the local interference scenario at the terminal. Note that optimal user selection can be very complex. First approaches with reduced complexity are proposed in [8].

Successive User Selection — In the following, a new heuristics for efficient user selection is proposed. It is evaluated in interference-limited macro-plus-small-cell scenarios measured in Berlin [10]. The scenario is shown in Fig. 1, left. The downtilt at the macrocells was set so that the vertical beams touch the ground after 0.33 times the inter-site distance. Channels to all cells were measured coherently. Small cells with disjoint coverage were placed at five locations having high intercell interference due to macrocells (magenta dots in Fig. 1, left).

The main new idea is denoted as successive user grouping. Note that the classical approach to search for orthogonal channel vectors [9] requires extensive CSI reporting. In order to reduce the feedback, we propose to select a first user in the small cell, typically at the cell edge. This user is grouped with other users selected randomly in the other cells included in the cluster. If all users experience performance gains compared to interference-limited transmission, user grouping is considered successful.

Otherwise, we replace users with reduced performance by other users selected randomly as well. Interestingly, in more than 80 percent of cases, all users in the cluster profit from JT CoMP after the first trial (red circle, Fig. 1, center). Suitable clusters, in which all users gain from cooperation, can often be formed after only a few iterations. While successive search has a minor effect in the small cell (Fig. 1, center top), it improves the clustering success rate and thus the spectral efficiency in the macrocells also involved in the cluster (bottom).

By selecting the best resource blocks and the best rank in each cell, the spectral efficiency even exceeds a well-known bound for cluster-based cooperation, where the spectral efficiency is limited only by out-of-cluster interference. Note that occasional beamforming gains when using a low rank were ignored when computing the bound (Fig. 1, right top). By forming the clusters and selecting the users as described above, obviously, the cluster size and all overheads due to pilots, feedback, and backhaul, and also the complexity of JT CoMP can be minimized, while the spectral efficiency approaches a theoretical limit [10]. Sophisticated algorithms are obviously important to achieve high JT CoMP gains.

Feedback Compression and Channel Prediction

In system-level simulations, for a 2 × 2 MIMO HetNet deployment with JT CoMP at 500 m distance between macro sites, spectral efficiencies of 6–7 b/s/Hz and 4–5 b/s/Hz are achieved in the small cell and in surrounding macrocells, respectively, assuming ideal CSI. This is more than 100 percent gain over multiuser MIMO, yielding less than 3 b/s/Hz. In reality, however, JT CoMP is very sensitive to channel estimation errors due to quantization and outdating of the CSI for mobile terminals. In the following, we consider the potential of both adaptive compression for the CSI feedback with controlled performance degradation and mitigation of the feedback delay by means of advanced channel prediction.

Feedback Compression — The overhead due to the feedback of the CSI for JT CoMP is commonly considered huge. As non-overlapping clusters are formed on different frequency subbands, the feedback can be limited to a fraction of the overall bandwidth [5]. Flexible clustering and successive user selection lead to a situation where the feedback requested from the users can be significantly reduced [10]. There is further potential by transforming the channel from the frequency domain, where the pilots are defined, to the time domain and selecting the most relevant paths [11]. This can be achieved by estimating the noise and out-of-cluster interference floor. The required quantization depends on this floor as well [12]. From these arguments, a combination of clustering, tap selection, and quantization is useful to compress the feedback.

We evaluated the combined potential of these approaches in [12]. Our reference case is similar to the JT CoMP link tested in [5]. A static feedback scheme is used where a terminal provides full CSI from its nearest 7 cells with 16 bits per real and imaginary values and per pilot. The number of pilots is equal to the cyclic prefix length. Tap selection yields a feedback reduction by a factor of 6, flexible clustering yields a factor of 3 due to the mean cluster size, and adaptive quantization yields a factor of 2. Note that these contributions are not multiplicative. Overall, the CSI feedback can be reduced by a factor of 15 compared to our reference case. Note that feedback compression can be implemented in real time [11, 12].

Channel Prediction — State-of-the-art prediction techniques like Kalman and Wiener filtering have the potential to make JT CoMP links more robust for CSI delays of a few milliseconds and at moderate mobility. Note that the precoder can be adapted to different reliabilities of the predicted channels. Kalman filters provide reliability information intrinsically, which can be reported semi-statically from the terminals [13, 14].

Doppler-delay-based prediction is a recent 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 frequency. From the recent channel history, these parameters can be estimated for each path. Next, the multi-path parameters are assumed to remain static over short periods of time. Then the channel can be predicted into the future by inserting the estimated parameters into the channel model. This approach has been studied using the standard spatial channel model (SCM) in [15] (Fig. 2, left). A significant improvement of the mean square error (MSE) for the CSI can be achieved, even at 30 km/h and 2.6 GHz, by using a few Doppler frequencies for each path.

In a further step, Doppler delay and Kalman prediction were both tested over measured channel data. Channels were measured coherently at a velocity up to 30 km/h at 2.66 GHz in 20 MHz bandwidth from three base stations in an urban macrocell scenario in Stockholm [13, references therein]. Thermal noise was set to –120 dBm per subcarrier, and 5-bit quantization was used for real and imaginary parts of the channel coefficient. For computing the Kalman filters, perfect CSI was assumed. For both methods, an order of 10 (numbers of filter poles or Doppler frequencies) was found to be sufficient.

Results shown in Fig. 2, center, are based on these measurements, using a channel history of 50 ms, CSI updates every 2 ms, and a prediction horizon up to 20 ms. For typical feedback delays between 5 and 10 ms, significant improvements of the MSE can be observed. The two methods follow different concepts. While the feedback overhead of the Doppler delay method is smaller, the sparse inverse discrete Fourier transform (DFT) used to extract the taps degrades the performance slightly. The Kalman filter is based on damped sinusoids instead of perfect ones, limiting the achievable prediction accuracy [14].

The improved CSI translates to better performance. Without prediction in moving scenarios, JT CoMP gains can even be negative. Using appropriate feedback intervals together with prediction, substantial gain can be realized by JT CoMP (Fig. 2, right). Note that irregularly, prediction fails. If prediction is also performed at the terminal, it can be compared with the latest measurements. The network can be informed about unusual prediction errors via a low-rate low-latency feedback channel.

Feedback compression, shorter feedback intervals, and a powerful predictor are regarded as important enablers for JT CoMP. A well designed feedback scheme reduces the overhead and counteracts the delay accumulated over the air and while the CSI is transported over the backhaul. Ultimately, such a scheme allows for higher mobility.

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Evolution to 5G: An Integrated Approach

In the following, we propose a combination of small cells, JT CoMP, and massive MIMO to increase the spectral efficiency in 5G.

Small Cells and Enhanced Indoor Coverage

A natural way to improve network capacity is to place further transmitters with moderate numbers of antennas at typical outdoor hotspot locations. As outlined above, more cells yield higher capacity if

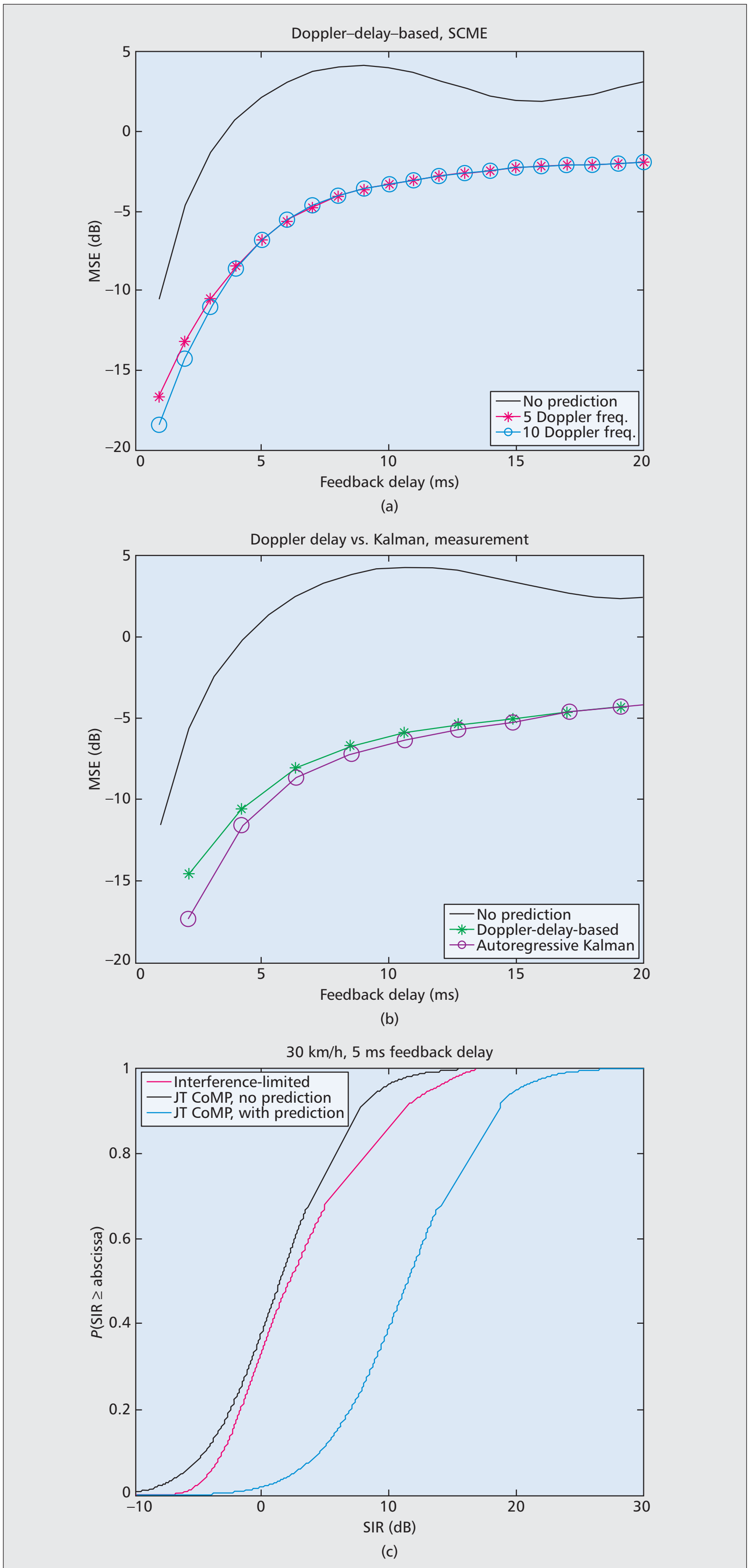

Figure 2. a) average precision of the CSI vs. the feedback delay with and without Doppler-delay-based prediction, assuming perfect CSI at the terminal, for SCM with 30 km/h. The oscillation with no prediction is due to temporal correlation; b) the same for measured channel data. An autoregressive Kalman filter without quantization for the CSI is used as a reference; c) performance with and without predicted CSI in a scenario with seven cells and three users.

the frequencies are reused. High-speed data coverage is improved, and the network diversity is increased. Shorter distances between base stations and terminals and a higher line-of-sight probability are further benefits. Deployment of small cells will probably start at hotspots leading to inhomogeneous cell layouts. More complex network planning is then required. Also adding small cells indoors is related to the use of more powerful enhanced wireless local area networks to overcome the strong outdoor-to-indoor penetration loss, which is often in the order of 10 to 20 dB and even more inside large buildings. On the other hand, less cooperation between indoor and macrocells is needed.

Massive MIMO and JT CoMP

Using many more antennas (i.e., massive MIMO) is commonly regarded as an alternative to JT CoMP. For very large numbers of antennas, it was shown recently that beamforming gains are so large that both intercell and inter-stream interference can be very low. Spectral efficiency can reach high values, like 100 b/s/Hz [4].

In combination with JT CoMP, macro-diversity gains can be exploited with more antennas than streams. This is useful to make the link more robust. The deployment of more antennas is appropriate to serve the increasing amount of users that can be expected if new services like device-to-device and machine-type communications are supported in the future. Note the fundamental trade-off between spatial multiplexing and diversity gains.

Active antennas and massive MIMO are related topics. However, the increased number of antennas is a big challenge for deployment at high-rise sites because the wind load and visibility are both increased. Today, macrocell panel antennas contain a stack of co-phased antenna elements that, all together, realize a fixed vertical beam with a certain down-tilt. Operating each antenna element in the panel independently enables more flexible vertical beamforming.

The synergy between massive MIMO and JT CoMP is intuitive if we assume a simple fixed grid of beams (GoB), shown in Fig. 3, left. A vertical GoB subdivides the cell into radial subsectors. The GoB can also be applied in the azimuth direction by increasing the number of columns in the array. Obviously, interference can be more localized using massive MIMO. With more antennas, interference is more likely between adjacent subsectors of the same site than between overlapping subsectors at different sites. Thus, less cooperation between the sites is needed, so the backhaul overhead associated with JT CoMP can be reduced.

In practice, more antennas need extra RF chains, extra analog-to-digital converters (ADCs, DACs), and more signal processing, which are not free. While antenna elements can be very cheap, extra costs for RF frontends and signal processing are more relevant. More research is needed to combine low-cost massive MIMO arrays with sufficient beamforming flexibility.

For 5G, we propose to combine massive MIMO with the interference mitigation framework as laid out above, and to increase the number of antenna elements only gradually so that the effort for a required performance target is minimized. In this way, massive MIMO will be used to

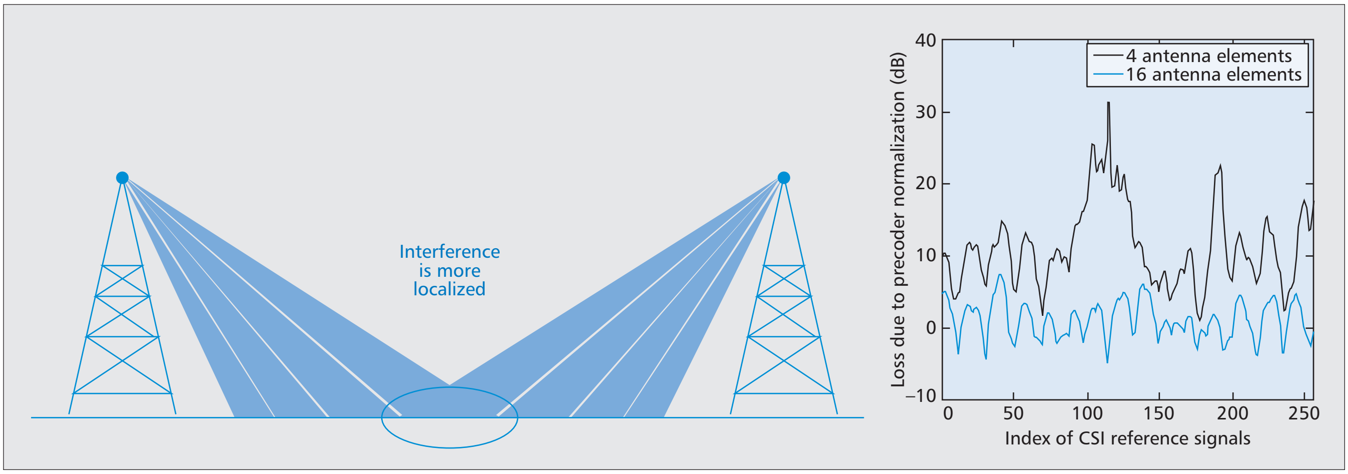

Figure 3. Left: Interference is more localized when using massive MIMO, which is beneficial for JT CoMP; right: moreover, interference suppression becomes more robust, as explained in the section "Initial Evaluation Results."

localize the interference and improve the rank of the overall channel matrix, while the use of JT CoMP overcomes residual intercell interference.

Altogether, adding more antennas at macrocells may be viable in a future 5G system. Benefits of massive MIMO are that there will be no extra site costs, it supports cell-wide or even intercell load balancing, extra backhaul costs are small, and more signal processing can be done at a single site.

Integrated Approach

Our envisioned 5G system concept is a sophisticated combination of these techniques, shown in Fig. 4. We expect that 5G will natively support small cells, JT CoMP, and massive MIMO to improve the spectral efficiency, besides enabling other techniques such as infrastructure and spectrum sharing between mobile operators.

The keys to operate the proposed system are centralized or distributed joint signal processing to coordinate the entire network. Moreover, a high-speed backhaul is needed to interconnect an increasing number of base stations and deliver the increasing amounts of data. Note that both high capacity and low latency are required in the backhaul to achieve high spectral efficiency in the proposed architecture [16].

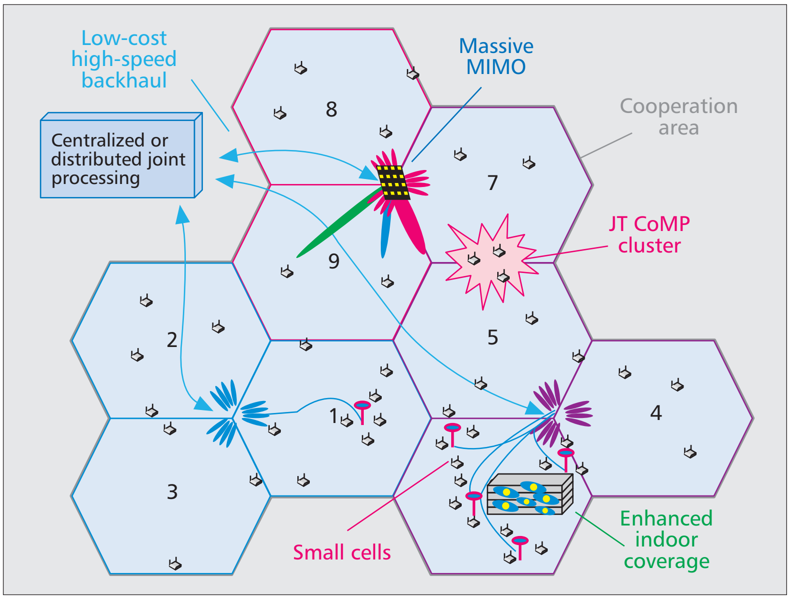

Figure 4. Integrated 5G mobile network concept including small cells, JT CoMP, and massive MIMO.

Initial Evaluation Results

As illustrated in Fig.1, the spectral efficiency of the proposed JT CoMP scheme is limited by out-of-cluster interference. When introducing small cells, frequency can be fully reused, and the same JT CoMP scheme can be used between macro- and small cells as between macrocells [10, 16]. Synchronization and sufficient backhaul capacity are obviously needed. Compared to multi-user MIMO in LTE, the spectral efficiency per antenna is increased by roughly 100 percent. Note that our current results do not include massive MIMO, which is for further research. For now, we show initial results to illustrate the enhanced robustness. The potential of the combined 5G approach is quantified using extrapolation.

By adding more distributed transmitters (small cells) or co-located antenna elements (massive MIMO), the most important limitations of efficient interference mitigation can be overcome. These are cases where the channel matrix has low rank (e.g., for parallel beams formed at a single site in the same direction toward co-located terminal antennas) and where the power of indoor terminals is low due to the high outdoor-to-indoor penetration loss.

With a low-rank channel matrix, more power is needed to separate the users. In Fig. 3, right, the normalization loss of a zero-forcing precoder is shown as a function of the CSI reference signal index (i.e., frequency). Results are obtained from ray-tracing simulations in the Munich area near the NSN campus. Three users spaced less than 50 cm from each other are jointly served over a distance of nearly 250 m. With 4 antenna elements, there is significant loss ranging from 10 to 20 dB. With 16 antenna elements, the average loss is 0 dB despite the closely spaced users. Simultaneously, there is an array gain of 6 dB. Spatial diversity makes JT CoMP obviously

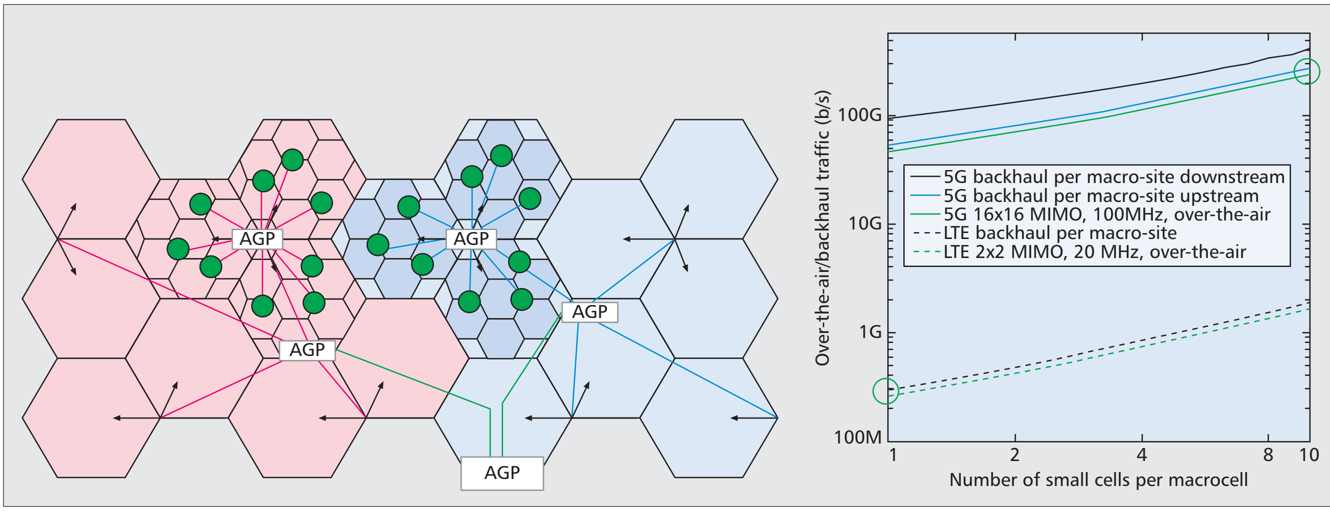

Figure 5. Left: Model of a heterogeneous mobile network using triple-sectored macro-sites. At two sites, small cells and a massive MIMO array are deployed yielding subsectors due to the GoB. Backhaul is organized as a physical tree. Information exchange between cells for JT CoMP is passed over direct logical links using the next common aggregation point (AGP); right: over-the-air and backhaul traffic vs. the number of small cells.

more robust in critical user constellations. Moreover, it reduces the impact of residual impairments such as prediction errors.

Finally, we extrapolate our current system-level results, and quantify the achievable throughput over the air and the required backhaul traffic in Fig. 5, right. We compare a triple-sectored 20 MHz 2 × 2 MIMO LTE macro-site scenario with a visionary 5G HetNet using 100 MHz spectrum, 10 small cells per sector, JT CoMP and a 16-element MIMO antenna array assuming an equivalent number of terminal antennas in each cell. In the HetNet, the small-cell traffic is aggregated at the nearest macrocell. Recommendations from the Next Generation Mobile Networks (NGMN) Alliance are used for backhaul estimation. Note that the inter-site ratio in [16] is smaller if more subsectors are formed using a GoB. With 16 × 16 enlarged MIMO, the backhaul overhead for JT CoMP is approximately halved.

We assume that over-the-air traffic can be scaled multiplicatively by using small cells (10×), JT CoMP (3×), more antennas (8×), and more spectrum (5×) compared to LTE. Using the combination of small cells, JT CoMP and massive MIMO as proposed here, 1000 times more traffic compared to a macrocell LTE deployment may be reached (circles, Fig. 5, right).

Conclusions

Our vision of a future 5G system includes a combination of existing and novel technologies like the deployment of small cells and enhanced local area networks and the joint use of both, and advanced interference mitigation based on JT CoMP and massive MIMO. We have quantified the benefits of integrating small cells into the JT CoMP concept as applied between macrocells, assuming that synchronization and backhaul are feasible. Using sophisticated clustering and user selection schemes, spectral efficiency is limited only by out-of-cluster interference. While channel aging tends to ruin the gains of JT CoMP for moving terminals, we have demonstrated that shorter reporting intervals combined with channel prediction enable high spectral efficiency. The combination of JT CoMP with massive MIMO is beneficial because more antennas make the link more robust, interference can be more localized, and the backhaul overhead can be reduced. Finally, we illustrate that 1000 times increase of mobile traffic is possible using a smart combination of all these concepts with reasonable effort. Also, we have outlined challenges for future research.

Acknowledgments

The authors acknowledge financial support by the European Union for the projects *ARTIST4G*, *METIS*, and *SODALES*, the German Federal Ministry of Education and Research for the project *CONDOR*, the German Research Council for the project *CoMPImpairments*, and the Swedish Research Council for the framework project *Dynamic Multipoint Wireless Transmission*. All colleagues in these projects are acknowledged for the inspiring work atmosphere and their contributions. Special thanks go to D. Aronsson, M. Grieger, S. Jaeckel, W. Mennerich, C. Oberli, T. Pfeiffer, F. Rosas, M Schlosser, and L. Schulz. The authors thank Alcatel Lucent Bell Labs and Ericsson Research for the measurement data used in this article.

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Biographies

VOLKER JUNGNICKEL [M'99] (volker.jungnickel@hhi.fraunhofer.de) received diploma and doctorate degrees in physics from Humboldt University, Berlin, in 1992 and 1995, respectively. He worked on semiconductor quantum dots and laser medicine before he joined the Fraunhofer HHI in 1997. Since 2003, he has been an adjunct lecturer at the Technical University of Berlin (TU Berlin), Germany, and project leader at HHI. Since 2013, he has been head of the metro, access, and in-house systems group. In his research, he has contributed to high-speed indoor optical wireless links, the first 1 Gb/s MIMO-OFDM mobile radio transmission experiments, the first real-time implementation and field trial for LTE, and the first coordinated multipoint experiments. He has authored and co-authored 160 conference and journal papers and 10 book chapters, and holds 24 patents. He won best paper awards at PIRC 2004, VTC 2010, and VTC 2013, and also the patent award of HHI in 2006. He has served on numerous TPCs, as Track Chair for VTC 2007 and 2013, as Chair of WSA 2009, and as an Associate Editor for *IEEE Photonics Technologies Letters*.

KONSTANTINOS MANOLAKIS (konstantinos.manolakis@tu-berlin.de) obtained a diploma degree from the Aristotle University of Thessaloniki, Greece, in 2004 and an M.Sc. degree from TU Berlin in 2007, both in electrical engineering with a focus on telecommunications. From 2006 to 2012, he was with Fraunhofer HHI. In 2012 he also joined the Telecommunication Systems Department of TU Berlin, where he is currently working toward his doctoral degree. His research interest is signal processing for communications in cellular networks with a focus on the impairment effects of coordinated multi-point transmission. He has authored and co-authored more than 25 conference and journal papers, and received a best paper award at IEEE VTC 2013.

WOLFGANG ZIRWAS (wolfgang.zirwas@nsn.com) obtained a diploma degree in communication technologies in 1987 from TU Munich, Germany. He joined Siemens central research laboratory for communications in Munich in 1987. Since 1996 he has contributed to and also partially led national and EU projects like ATMmobil, COVERAGE, 3GeT, ScaleNet, WINNER, ARTIST4G, and METIS. His research interests include multihop, MIMO, cooperative antennas, and OFDM. At the end of 2004, he led the project that realized the 1 Gb/s MIMO-OFDM world record. During 2006–2007, he demonstrated LTE and virtual MIMO, and attended 3GPP LTE standardization meetings on MIMO. He has authored and co-authored 120 conference and journal papers, contributed to four books, and filed more than 200 patents. He was the Inventor of the Year within SIEMENS and NSN in 1997, 2007, 2008, and 2009, and received a best paper award at FuNeMS in 2012. He served on the TCPs of European Wireless, PIMRC, and WDN-CN 2012, and as Associate Editor of the *Scientific World Journal*.

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VOLKER BRAUN (volker.braun@alcatel-lucent.com) has been with Alcatel-Lucent Bell Labs (formerly Alcatel Research & Innovation), Stuttgart, Germany, since 1999. He led the development of the base station software for the HSPA fast radio resource management, and defined and integrated an LTE pre-standard prototype system used for early customer mobility trials. He further pioneered the concept of outdoor infrastructure small cells. Currently he is working on various 5G research aspects.

MORITZ LOSSOW (moritz.lossow@telekom.de) received B.Eng. and M.Eng. degrees in communication and information engineering from the University of Applied Sciences of Berlin in 2011 and 2012, respectively. Until 2013, he was with the Wireless Communications and Networks Department at Fraunhofer HHI, where he investigated cooperative processing in heterogeneous cellular networks. In 2013, he joined the Wireless Technology and Networks Department, Deutsche Telekom AG, Telekom Innovation Laboratories, where his current research interests include statistical data traffic modeling and MIMO techniques in cellular networks.

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TOMMY SVENSSON [S'98, M'03, SM'10] (tommy.svensson@chalmers.se) received a doctoral degree in information theory in 2003. He is associate professor for communication systems at Chalmers University, where he is leading the research on air interface for wireless access and wireless backhauling networks for future wireless systems. He has been working with Ericsson AB on core networks, radio access networks, and microwave transmission products. His main research interests are in design and analysis of physical layer algorithms, multiple access, resource allocation, cooperative systems, and moving relays/cells/networks. He has co-authored more than 100 conference and journal papers, two books, and more than 30 EU projects reports. He is responsible for the Master's program on communication engineering at Chalmers, and serves as Chairman of the Swedish joint IEEE Vehicular Technology, Communications, and Information Theory Societies chapter.

Our vision of a future 5G system includes a combination of existing and novel technologies like the deployment of small cells and enhanced local area networks and the joint use of both, advanced interference mitigation based on JT CoMP, and massive MIMO.