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MIMO Technologies for the Wireless Future

G. Bauch, DoCoMo Euro-Labs, Germany

A. Alexiou, Bell Labs, Alcatel-Lucent, UK

***Abstract*— Future wireless systems are expected to support high data rates of 1 Gbit/s or more in a variety of scenarios. A key technology in order to achieve the required high spectral efficiency is the application of multiple input multiple output (MIMO) techniques, which exploit spatial diversity, array gain or spatial multiplexing gain. Another source of diversity – inherent to wireless systems- is that of the multiuser diversity. Multiuser (MU) MIMO algorithms combine both MIMO gains with multiuser diversity benefits. Although MU MIMO techniques have been extensively studied and were shown to provide considerable average cell throughput gains, they often prove inadequate to cope with intercell interference and can only offer poor cell edge performance. Network coordination (multisite MIMO) can be applied in this case, which can achieve significant improvements for the users including those at the cell edge, based on coordinated transmission and reception by multiple base stations. In this paper we present an overview of the most promising MIMO technologies and discuss their relative merits and requirements.**

I. INTRODUCTION

THE successful adoption of advanced technologies, such as MIMO, in future wireless systems design, as a means to address the challenging spectral efficiency, flexibility and adaptability requirements, is not only a matter of devising sophisticated signal processing, resource allocation or cross layer techniques but also and most importantly a matter of realistic consideration of the *overall network performance dynamics* and the *overhead signaling bandwidth constraints* [1].

Following this line of thought, we present in this paper a brief overview of the MIMO techniques currently considered in the evolving standards (such as 3GPP-LTE), namely open and closed loop single user (SU) MIMO techniques. Performance targets to address IMT-Advanced requirements are discussed and promising candidate MIMO technologies for future wireless systems design are explained, namely multiuser MIMO for average cell throughput improvements and multisite MIMO for average cell and cell edge throughput enhancements.

II. MIMO IN 3GPP-LTE

MIMO is an essential ingredient of 3GPP-LTE [1], where a 2 transmit and receive antenna scheme is considered to be the baseline downlink configuration. Four transmit and receive antennas are also supported. For the uplink, transmission with only one transmit antenna including antenna selection is supported. For the downlink, the standard contains both transmit diversity and spatial multiplexing.

For open loop transmit diversity, basically a space-frequency Alamouti scheme is used as depicted in Fig. 1 [3]. Together with a simple linear combiner at the receiver, this scheme essentially produces an effective single-input single-output channel, the channel coefficient of which is given by the sum of the squared magnitudes of the channel coefficients from all transmit to all receive antennas. The constructive interference leads to an effective channel, which is more stable than an individual channel from a transmit to a receive antenna.

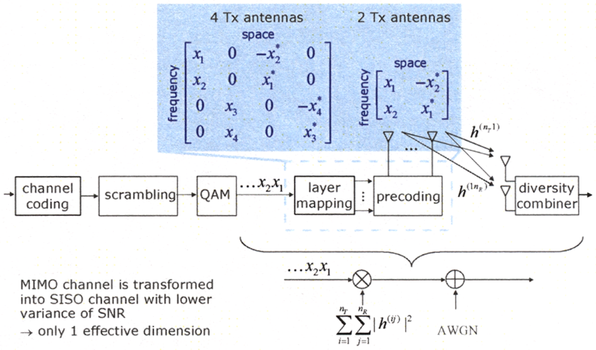

Fig. 1: Space-frequency transmit diversity in 3GPP-LTE.

In case of 4 transmit antennas, the LTE standard just uses different subcarriers and antenna switching with two Alamouti schemes.

Alamouti-based transmit diversity does not directly increase the data rate by adding simultaneously transmitted spatial data streams. True spatial multiplexing with linear precoding and a variable number of spatial streams (layers) is also supported in 3GPP-LTE. The terminal chooses the preferred precoder from a codebook and feeds the respective codebook index back to the base station. As an example, the codebook for 2 Tx antennas and the respective beampatterns for an antenna spacing of half wavelength are depicted in Fig. 2.

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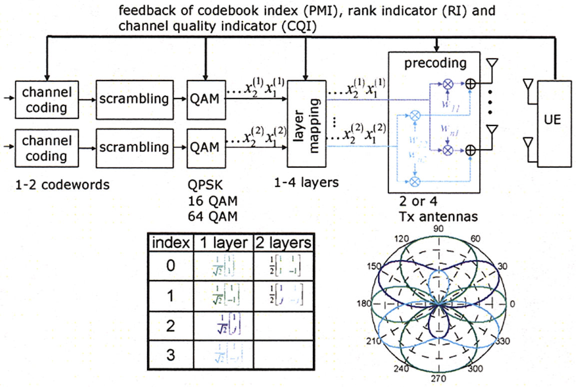

index	1 layer	2 layers
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&1\\1&-1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1&1\\j&-j\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	

Fig. 2: Closed loop precoding for 2 Tx antennas in 3GPP-LTE.

A third MIMO variant called large delay cyclic delay diversity (CDD) precoding is used for open loop precoding. Here, the precoder is determined by

$$\mathbf{P}(i)=\mathbf{W}(i)\mathbf{D}(i)\mathbf{U},$$

where the matrices are taken from the codebook in Fig. 3 and i corresponds to the subcarrier index. Besides precoding, L columns of the matrix $\mathbf{W}(i)$ are used in order to produce L virtual antennas, where L is the number of layers. The diagonal matrix $\mathbf{D}(i)$ introduces a virtual antenna dependent phase shift, which can be interpreted as a virtual antenna dependent cyclic delay in the time domain.

layers	$\mathbf{U}$	$\mathbf{D}(i)$	$\mathbf{W}(i)$
2	$\begin{bmatrix}1&1\\1&e^{-j2\pi/2}\end{bmatrix}$	$\begin{bmatrix}1&0\\0&e^{-j2\pi i/2}\end{bmatrix}$	2 Tx: $\frac{1}{2}\begin{bmatrix}1&0\\0&1\end{bmatrix}$ 4Tx: $\mathbf{W}_n=\mathbf{I}_4-2\mathbf{u}_n\mathbf{u}_n^H/\mathbf{u}_n^H\mathbf{u}_n,\ n=12,\dots,15$
3	$\begin{bmatrix}1&1&1\\1&e^{-j2\pi/3}&e^{-j4\pi/3}\\1&e^{-j4\pi/3}&e^{-j8\pi/3}\end{bmatrix}$	$\begin{bmatrix}1&0&0\\0&e^{-j2\pi i/3}&0\\0&0&e^{-j4\pi i/3}\end{bmatrix}$	$\mathbf{W}_n=\mathbf{I}_4-2\mathbf{u}_n\mathbf{u}_n^H/\mathbf{u}_n^H\mathbf{u}_n,\ n=12,\dots,15$ Householder codebook
4	$\begin{bmatrix}1&1&1&1\\1&e^{-j2\pi/4}&e^{-j4\pi/4}&e^{-j6\pi/4}\\1&e^{-j4\pi/4}&e^{-j8\pi/4}&e^{-j12\pi/4}\\1&e^{-j6\pi/4}&e^{-j12\pi/4}&e^{-j18\pi/4}\end{bmatrix}$	$\begin{bmatrix}1&0&0&0\\0&e^{-j2\pi i/4}&0&0\\0&0&e^{-j4\pi i/4}&0\\0&0&0&e^{-j6\pi i/4}\end{bmatrix}$	$\mathbf{W}_n=\mathbf{I}_4-2\mathbf{u}_n\mathbf{u}_n^H/\mathbf{u}_n^H\mathbf{u}_n,\ n=12.\dots,15$ Householder codebook

Fig. 3: Codebook for large delay CDD precoding in 3GPP-LTE.

For the example of 2 Tx antennas, the effective precoder is given by

$$\mathbf{P}(i)=\begin{bmatrix}1&0\\0&e^{-j2\pi i/2}\end{bmatrix}\begin{bmatrix}1&1\\1&e^{-j2\pi/2}\end{bmatrix}=\begin{cases}\begin{bmatrix}1&1\\1&-1\end{bmatrix} & \text{for even } i\\[2ex] \begin{bmatrix}1&1\\-1&1\end{bmatrix} & \text{for odd } i.\end{cases}$$

In this case we have a beam switching between adjacent subcarriers, which introduces diversity. Therefore, CDD precoding is mainly advantageous for higher mobility. In case of 4 Tx antennas, the matrix $\mathbf{W}(i)$ is cyclically changed along groups of subcarriers in order to provide additional diversity.

III. PERFORMANCE TARGETS AND MIMO FOR IMT-ADVANCED WIRELESS SYSTEMS

The 3rd Generation Partnership Project (3GPP) has recently drafted its view on requirements for IMT-Advanced wireless systems, which are expected to be commercialized around the year 2015 [4]. Some key figures are summarized in Fig. 4.

Compared to 3GPP-LTE, key parameters such as average user spectrum efficiency, cell spectrum efficiency and cell-edge user spectrum efficiency are expected –within IMT-Advanced- to be improved by a factor of 2-3. This will require a broader, scalable bandwidth of up to 100 MHz.

There is wide agreement that the required improvement in terms of spectrum efficiency can only be achieved by application of enhanced MIMO technologies. This basically means using more antennas both at the base stations and the terminals.

	3GPP-LTE		3GPP-LTE-Advanced
Peak data rate	DL:150 Mbps (2x2 MIMO) UL: 75 Mbps		DL:1 Gbps for nomadic/local access (100 Mbps for high mobility) UL: 500 Mbps (30 Mbps)
Peak spectrum efficiency	DL: 7.5 bps/Hz UL: 3.5 bps/Hz	x 4 ➡	DL: 30 bps/Hz UL: 15 bps/Hz
Average user spectrum efficiency	DL: 0.16 bps/Hz UL: 0.086 bps/Hz	x 3 ➡	DL: 0.48 bps/Hz/cell UL: 0.26 bps/Hz/cell
Cell spectrum efficiency	DL: 1.63 bps/Hz/cell UL: 0.86 bps/Hz/cell	x 2 ➡	DL: 2 (2x2) – 4 (4x4) bps/Hz/cell UL: 1 (1x2) – 2 (2x4) bps/Hz/cell
Cell edge user spectrum efficiency	DL: 0.05 bps/Hz UL: 0.028 bps/Hz	x 2 ➡	DL: 0.07 (2x2) – 0.12 (4x4) bps/Hz UL: 0.04 (1x2) - 0.07 (2x4) bps/Hz
Bandwidth	Scalable 1.4-20 MHz		Scalable up to 100 MHz

Fig. 4: Performance targets for 3GPP-LTE-Advanced.

While the baseline in 3GPP-LTE is 2 x 2 MIMO, i.e. 2 transmit and 2 receive antennas, the baseline in IMT-Advanced will most likely be 4 x 2 and 4 x 4 MIMO. Interestingly, even significantly higher numbers of antennas at the base station, e.g. 8-12 antennas, are not considered to be out of scope by many companies. Since the terminal size and complexity should be kept reasonably small, such a high number of antennas is not expected at the terminal. As far as the downlink is concerned, this results in a constellation with significantly more transmit than receive antennas, which calls for application of multiuser MIMO, where the receive antennas are distributed over several users. The key problem in MU-MIMO is that receive antennas over several users do not - in general- cooperate and, therefore, inter-user interference needs to be dealt with by means of signal processing at the transmitter.

While MU-MIMO is easier to apply in hotspot or indoor environments, where a high density of users allows for exploitation of multiuser diversity and the channel information reliability is sufficient, another key problem in IMT-Advanced systems, that of sufficient coverage and improvements for the cell edge users performance in various environment, including wide area / high mobility scenarios, can be addressed by new architectures, such as relaying and multisite MIMO, where different base stations antennas act together as a single network antenna array.

In the following two sections, we will discuss MU-MIMO and multi-site MIMO as two key technologies for future wireless systems, which go beyond MIMO as we have it in already standardized or even commercialized systems.

IV. MULTIUSER MIMO

A situation as anticipated for IMT-Advanced wireless systems, where we have many more transmit than receive antennas calls for the application of MU-MIMO. Here, the antennas are essentially distributed over several users, which are served at the same time on the same frequency band and separated by means of spatial processing. In contrast, single-user (SU) MIMO allocates all spatial resources in a particular frequency band at a time to the same user (Fig. 5). Significant gains over SU-MIMO in terms of sum capacity or cell throughput can be achieved as indicated in Fig. 6

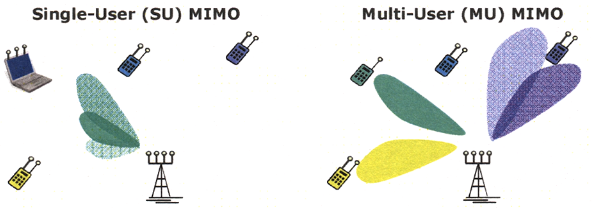

Fig. 5: Single-user (SU) vs. multi-user (MU) MIMO.

For uplink (see Fig. 7), MU-MIMO transmission is mainly a scheduling problem. In fact, similar detection methods as in single-user MIMO can be applied. Particularly, the inter-user interference can be resolved by receiver processing.

In the downlink, the problem is more challenging: Since a particular user may have access to only a limited number of receive antennas, he is unable to resolve all the spatial streams that may be transmitted by the base station. Consequently, the transmitter needs to take care of the inter-user interference. This requires channel state information (CSI) at the transmitter.

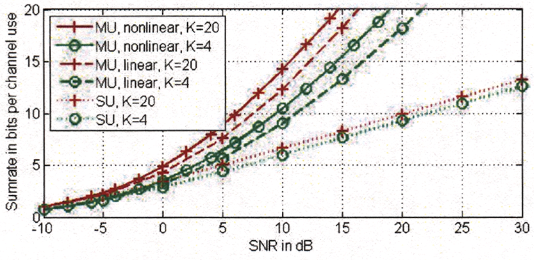

Fig. 6: Linear vs. non-linear multi-user (MU) MIMO and single-user (SU) MIMO. Semi-correlated channel, 4 Tx antennas, 1 Rx antennas per user.

In practical systems, only quantized or incomplete CSI (e.g. outdated or subject to channel estimation errors) will be available at the transmitter. As we will show, the accuracy of CSI is decisive for the gains achievable by MU-MIMO over SU-MIMO.

Potential benefits of MU-MIMO over SU-MIMO are the following:

Including the spatial domain into the scheduling process offers one additional degree of freedom, which allows for better exploitation of multiuser diversity. Multiuser diversity refers to the gain achieved by allocating a resource unit in time, frequency and space to the user with the highest capacity on this resource unit.

In SU-MIMO, the number of spatial dimensions that can be exploited is limited by the number of antennas at the terminal. Potential spatial dimensions are wasted in the likely case that the terminal has smaller number of antennas compared to the base station. In MU-MIMO, the full number of spatial dimensions can be exploited. This may result in significant gains in terms of sum capacity over SU-MIMO.

Moreover, in SU-MIMO, there may be only one or two strong spatial dimensions, whereas the other spatial dimensions are relatively weak as indicated by the different size of the beams on the left hand side of Fig. 5. This is particularly true in case of spatial correlation and Line of Sight (LOS). In MU-MIMO, we can pick the strongest spatial dimensions among all users. This results in a sum capacity gain particularly in case of low rank channels.

The full potential of MU-MIMO can be exploited when perfect knowledge of the instantaneous realizations of the channels to all users is available at the transmitter and non-linear precoders based on dirty paper coding (DPC) [5] are used. The optimum capacity achieving solution as given in [11] is prohibitively complex. However, a couple of heuristic algorithms exist, which construct the transmit signal by successive encoding (see e.g. [6] and references therein). Those schemes theoretically allow close to capacity performance. However, practical implementations of DPC are still a research problem, particularly with limited CSI.

Therefore, linear precoders seem to be more appropriate for real systems. Interestingly, linear MU-MIMO schemes can get fairly close to the capacity limits of non-linear MU-MIMO as indicated in Fig. 6. Moreover, linear precoders can more easily be used with limited CSI at the transmitter.

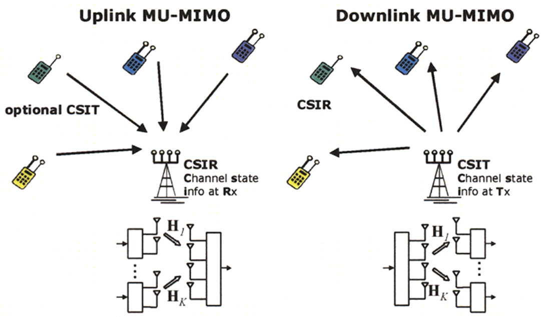

Fig. 7: Uplink vs. downlink MU-MIMO.

A simple version of MU-MIMO with only a few bits feedback per user is discussed for 3GPP-LTE. Here, each user feeds back the codebook index of a preferred precoder. The same precoders, as the ones used for SU-MIMO, can be used for MU-MIMO. The base station then schedules those users with sufficiently orthogonal precoders.

Another MU-MIMO option allowing for more flexibility in the precoder selection is a feedback where the codebook contains quantized versions of the channel itself rather than precoding vectors [8]-[10]. First, all users estimate their channel based on pilot symbols in a common pilot channel. Then, the goal of each user is to choose the codebook entry with the minimum Euclidean distance to the compound channel, which consists of the physical channel $\mathbf{H}_k$ itself and the assumed receive filter $\mathbf{w}_k^T$.

However, since the precoder used during the data transmission phase is not yet known to the users, they have to make an assumption on the receive filter $\mathbf{w}_k^T$. Basically, the codebook entry is chosen, which corresponds to the minimum angle with the subspace span($\mathbf{H}_k^T$), where $\mathbf{H}_k$ is the channel matrix for user k. This is justified since the compound channel is a linear combination of the columns of $\mathbf{H}_k^T$ (or, equivalently, the rows of $\mathbf{H}_k$). The respective codebook index is fed back to the base station together with an SINR estimate as quality indicator.

The base station collects the feedback from all users. It groups users, which are scheduled according to a sum capacity maximization criterion, and computes *zero-forcing precoding* vectors. Since the actual precoders are not known to the users, dedicated pilot symbols have to be transmitted to the user over the precoded channels. Based on the pilots, the users determine the compound channel and the actually used receive filter, which may be different from the assumed filter $\mathbf{w}_k^T$ used in order to determine the fed back codebook entry.

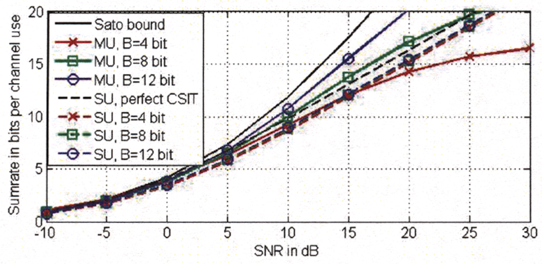

Fig. 8: MU-MIMO vs. SU-MIMO with limited feedback of B bit per user. Semi-correlated channel, 4 Tx antennas, 2 Rx antennas per user.

In Fig. 8, we compare the achievable rates for the zero forcing MU-MIMO technique and SU-MIMO with the same number of feedback bits per user. We restrict the MU-MIMO scheme to schedule only one spatial stream per user, which is the working assumption in 3GPP-LTE and minimizes the required number of feedback bits. In contrast, SU-MIMO allows for spatial multiplexing of a particular user with two spatial streams. For MU-MIMO, we allow for a maximum of 4 spatially separated users. For each case, the codebook type (DFT or random), which had been identified as the most suitable choice in other simulations, is used.

It can be observed that for a low number of feedback bits (4 bits per user), SU-MIMO outperforms MU-MIMO at least at moderate and high SNR. I.e., there is a trade-off between multiuser diversity and inter-user interference. However, if we spend only a few more bits for the feedback (8-12 bits per user), MU-MIMO clearly outperforms SU-MIMO and approaches the Sato bound.

Extension of the ZF in the multi-receive antenna case, where multiple spatial streams are transmitted to each user with no inter-user interference, has been studied in [14][15], following a *block diagonalization* (BD) approach.

To fully exploit multi-antenna / multiuser diversity gain, a linear precoding technique, called *multiuser eigenmode transmission* (MET) has been proposed in [16]. MET achieves performance near the optimum capacity-achieving dirty paper coding by simultaneously transmitting multiple spatially multiplexed streams to multiple users. The transmitter requires estimates of the users' channels to form beams for each stream. For perferct CSI a zero-forcing type beamforming results in zero inter-user interference. MET was generalized in [17] for the limited feedback case by introducing a minimum mean-squared error (MMSE) receiver to mitigate the effects of interbeam interference and *optimize the trade-off between multiuser diversity and inter-user interference.*

For a fixed number of feedback bits, MET with partial CSI was compared in [17] with a technique performing spatially matched beamforming, which relies on the MMSE receiver to mitigate inter-user interference. It was shown that MET provides substantial gains for feedback bits exceeding a certain number (e.g. greater than 4), that depends on the number of antennas, users and SNR conditions. For very low number of feedback bits (e.g. 2), CSI is not sufficient for MET transmit processing and relying on receive processing, as in the spatially matched beamforming case, provides better performance.

It has become apparent that the efficiency of MU-MIMO techniques is closely associated with the available CSI reliability. Their application to TDD or hotspot and indoor environments is expected to offer promising gains, especially in the presence of a large number of users, which is necessary in order to benefit from multiuser diversity. In FDD systems and/or in highly dynamic environments, with respect to channel variability, CSI reliability may be limited and *efficient feedback design* becomes critically important.

Addressing the challenge of efficient feedback design, a novel approach has been proposed in [18], where a framework for hierarchical quantization is first developed and then applied in the case of MET MU-MIMO scheme. *Hierarchical feedback* achieves adaptivity to CSI reliability by allocating a fraction out of the total number of feedback bits for updating the quantization level and the remaining feedback bits for updating the actual MU-MIMO codewords. Comparison of this approach with random and DFT codebooks demonstrates substantial improvements in terms of feedback requirements for a certain throughput performance target.

V. MULTISITE MIMO

As discussed in the previous section, MU-MIMO has been shown to considerably improve average cell throughput (over SU-MIMO) in a variety of scenarios, taking advantage of the spatial and multiuser diversity at the expense of additional feedback signaling bandwidth requirements. The tradeoff between MU-MIMO gains and signaling requirements can be further improved by optimizing the use of feedback, for example by means of hierarchical quantization. Nevertheless, in a capacity-limited situation, intercell interference may be the limiting factor, not only by affecting the average cell performance in a multi-cellular network but also –and most importantly- by prohibitively degrading the cell edge performance.

In conventional cellular networks intercell interference is usually addressed by frequency planning, soft handoff, intelligent receiver structures and resource allocation. High spectral efficiency requirements in future systems both for average cell and cell edge cases, as discussed in Section III, impose more challenging targets for intercell interference management. *Network coordination* has been proposed in [19] as a way to address this challenge by introducing coordinated transmission across base stations in the entire network (Fig. 9). In this case the resulting performance is equivalent to that of a MU-MIMO (multi-point to multi-point) system with a distributed antenna array consisting of all the antenna arrays on all base stations. More than a factor of 10 of improvements in spectral efficiency is reported in [19], when full coordination and 4x4 antenna systems are assumed, compared to the baseline of uncoordinated transmissions with single antenna terminals.

These impressive enhancements can only be realized under the assumptions of perfect channel knowledge (for all interfering channels) and sufficient backhaul bandwidth to allow for the exchange of control and data signaling among all base stations through the centralized control unit. *Realistic backhaul constraints* make full coordination unaffordable in practical networks and to address this challenge a number of approaches have been proposed on *partial coordination.*

In [20][21] coordination is applied only to a subset of selected users, achieving the best possible capacity and fairness improvements under strongly constrained backhaul requirements between sites. The grouping of users is implemented considering only average and not instantaneous CSI. Partial coordination in the form of *cell clustering* is studied in [22], for a certain power allocation and beamforming scheme. As opposed to the static clustering approach in [22], *dynamic clustering* is proposed in [23], where for the users scheduled to be served at each time slot, the best base station group is selected for coordination.

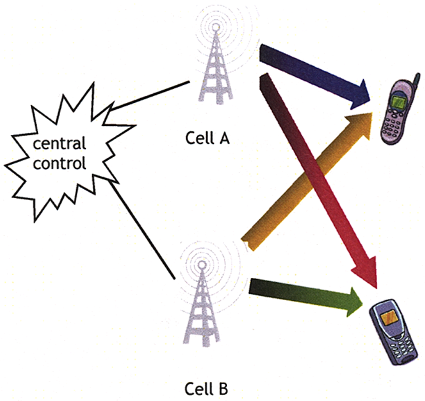

Fig. 9: Intercell coordination (Multisite MIMO concept)

The challenge of multisite MIMO is to identify a framework for optimization of the tradeoff between network coordination gains and backhaul signaling requirements. The main parameters involved in this optimization are the effective network size selection (static/dynamic clustering) and the coordination decision metrics and their granularity (instantaneous/average CSI, SINR/fairness, etc).

VI. CONCLUSIONS

In this paper we discussed the recent developments in the area of MIMO technologies and presented an overview of the most promising techniques for future wireless systems along with the associated implementation challenges. Substantial average cell throughput and cell edge throughput gains can be achieved with the adoption of MU-MIMO and multisite MIMO architectures respectively. Nevertheless these gains heavily depend on the efficiency of feedback signaling and the underlying complexity/cost and backhaul constraints.

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