Scaleable Network Multicast for Cooperative Base Stations

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***Abstract*—Cooperative joint transmission and detection algorithms have a high potential to increase the capacity of cellular radio systems. This paper investigates efficient network layer protocols to realize such cooperation over a heterogeneous, bandwidth-limited backhaul. Target systems are MIMO-OFDM cellular communication systems with flat hierarchy (no central unit), and we take 3GPP LTE as example. The proposed architecture uses IP multicast for stations receiving the same information and is scaleable by dynamically cooperating only on frequency subbands. SINR and mobility thresholds are used to first cooperate for critical cell-edge users with low mobility, where most interference reduction gain is to be expected.**

I. Introduction

Cellular communication system throughput is known to be interference limited. Modern systems like 3GPP LTE [1] use orthogonal multicarrier modulation (e.g. OFDMA and SCFDMA) to avoid intracell interference. The remaining factor limiting system throughput is intercell interference.

Against intercell interference, base station cooperation has recently gained interest. A high-throughput low-delay backbone between base stations is assumed, so that information can be exchanged in realtime to reduce, avoid or cancel interference from neighbouring base stations respective terminals [2] [3].

Cooperation can be done on several levels, where the main approaches are interference mitigation, multicell scheduling and joint signal processing. In the draft LTE standard, cooperation is limited to interference mitigation, where base station schedulers negotiate transmit power restrictions on certain frequency subbands, with a time granularity of several seconds.

A. Joint Signal Processing

Joint transmission and detection enables the benefits of a larger number of antennas without the high costs of actually building them: antennas of neighbouring base stations are shared over a high-speed network connection. Applicable joint precoding algorithms are e.g. described in [3]. Joint detection in uplink aims at utilizing all received energy at all base stations [2] (see fig. 3).

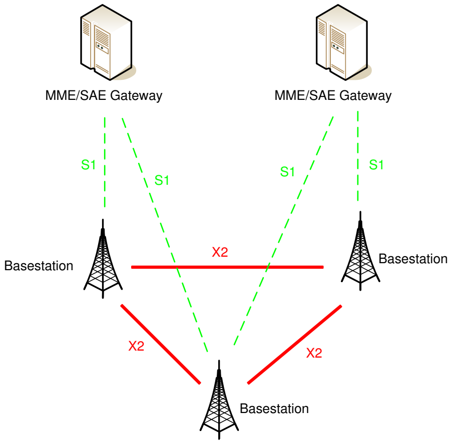

Fig. 1. S1 and X2 interfaces in the LTE draft standard [1].

B. Overview of Current System

The LTE system base stations support two logical interfaces over their IP connection (see fig. 1). The first one is the S1 interface to the base station's gateway (featuring a tunnel protocol like GTP [4]), the other is the X2 interface to other basestations. In the LTE protocol stack, base station cooperation (interference mitigation) belongs to the radio resource control (RRC) entity, information is exchanged over the X2 interface. The protocol stack for S1 is shown in fig. 2.

C. Cancelling Intercell Interference by Antenna Sharing

In [2] and [3] a central signal processing unit is assumed, treating the antennas of all base stations as one large array. In the flat LTE hierarchy, there is no central unit available. Joint signal processing has to be done distributedly in the base stations. Baseband samples have to be exchanged over the normal IP infrastructure, e.g. using UDP/IP.

This paper deals with base station cooperation for joint transmission and detection. It applies the idea to a practical system with flat hierarchy like LTE and deals with the necessary flows of cooperation information between different stations and a protocol to efficiently realize this. An initial performance estimation is done by system level simulation.

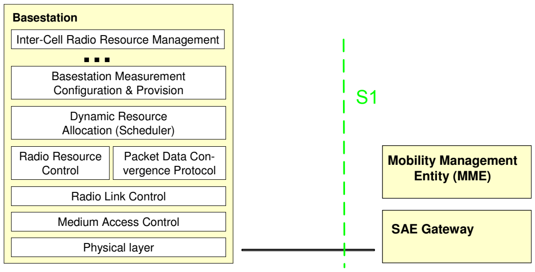

Fig. 2. Protocol stack over the S1 interface [1].

II. CONSTRAINTS FOR PRACTICAL SYSTEM

A. Area Limitation due to Cyclic Prefix

The size of the geographical area in which joint signal processing is possible for a MIMO-OFDM system like LTE is limited by the length of the OFDM cyclic prefix (CP). In normal OFDM systems the CP guards against intersymbol interference: the channel response of the previous OFDM symbol decays in the CP. In cooperative MIMO-OFDM systems, the CP must not only be long enough to compensate channel delay spread, but also to compensate propagation delay differences to different stations. So on the one hand the CP must be prolonged to allow for cooperation, on the other hand it is not to be prolonged too much, because it is overhead. It may be set to allow for cooperation with one or two rings of base stations in an urban deployment.

B. Uplink and Downlink Differences

There are several differences concerning joint signal processing for uplink and downlink. First, joint transmission in downlink needs coherent transmitters, while for joint detection in the uplink several base stations can independently synchronize to a transmitting terminal. Then, joint transmission needs channel state information at the transmitters, which requires a feedback control channel using precious uplink resources. For downlink there are two possibilities for exchanging information between base stations: either transmit data together with precoding information and scheduling information can be exchanged, then baseband samples would be decentrally computed (saves backhaul bandwidth). Or 'centrally' computed baseband samples could be exchanged.

Due to the downlink problem of necessary channel knowledge at the transmitter, in the following we focus on joint detection in the uplink. In the uplink, received baseband samples are exchanged between base stations.

C. Interference Situation

In [5], the interference situation in an urban deployment has been investigated. There are typically many interferers, and the amount of interference caused is dependent on the position of the station and whether there is a line of sight connection between the stations or not.

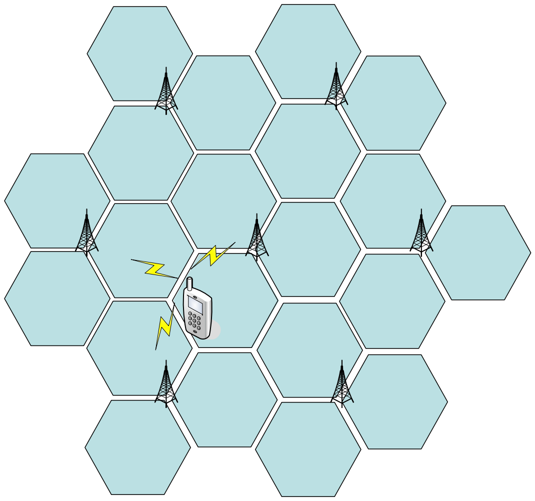

Fig. 3. Joint detection also uses signal energy received at remote base stations.

D. Network Bandwidth and Computational Power

Other factors limiting practical joint detection possibilities (the number of cooperating stations) are network bandwidth and computational power. As linear MIMO detection includes matrix inversion, the algorithm basically scales cubically with the number of jointly processed antenna signals. The backhaul connections of base stations are typically heterogeneous, a fixed amount of bandwidth available for sample exchange cannot be assumed.

E. What is needed?

An architecture with fixed mapping of areas of joint processing into the hexagonal grid is given in [6]. The subsections above show that the cooperative joint detection system should be dynamically scaleable in terms of needed network bandwidth and in terms of which stations cooperate. Further it is suggestive to have overlapping areas of joint processing to allow for interference reduction at all possible terminal positions.

III. PROPOSED ARCHITECTURE

A. Multicast Received Samples to Dynamically Selected Cooperation Group

For detection, a base station also uses receive samples of neighbouring stations provided over the network. It processes a larger number of antenna signals, but the same number of data streams as without cooperation. Energy received at remote antennas is also used for detection, interference by other terminals is cancelled (see fig. 4).

Receive samples are transmitted over the network to several neighbouring base stations, areas of cooperation therefore overlap. The groups of cooperating stations may differ on different subbands, as in OFDMA and SC-FDMA each user is normally scheduled only on a part of the whole frequency band. Each base station can be seen as a virtual central unit processing samples from its own antennas and antennas of neighbouring stations.

As the same information (receive samples) is transmitted to several recipients (base stations), multicast makes sense to reduce the number of packets a station has to process. Multicast uses special IP addresses describing multicast groups. Joining and leaving a multicast group is controlled for IP version 4 by the Internet Group Management Protocol (IGMP), for version 6 by the Internet Control Message Protocol (ICMPv6). The important aspect of multicast is that the administration is done in the routers. They use special multicast routing protocols (e.g. DVMRP) to establish a distribution tree for packets of a group. A transmitting station does not need to know which and how many stations are listening, packets are multiplicated by the routers.

Using multicast for sample exchange transfers some of the work from base stations to the routers. Stations wanting to use samples of one specific base station form a multicast group. A base station can belong to several groups. Computation (joint detection) in this architecture is partly redundant, because there is no actual central unit. The number of antenna signals a base station processes may differ for different subcarriers (MIMO processing on different subcarriers is independent for OFDM). The exchange of frequency domain samples avoids transmitting guard band samples and allows for scaling the necessary backhaul bandwidth.

B. *Considering Terminal Mobility*

In one cell, dedicated pilot symbols are used for different transmit antennas to allow the receiver to estimate the channel matrix per subcarrier. When one antenna transmits a pilot, the other antennas don't transmit. For multiple cells dedicated pilots are not practicable (pilots are overhead). Joint channel estimation without dedicated pilots is possible, but the performance is of course worse [7]. Filtering in time and frequency is done for joint channel estimation. If it is known that the channel varies slowly (low mobility), longer filtering over time is possible, yielding better channel estimation performance: joint channel estimation performance is dependent on mobility. As channel estimation performance limits detection performance, a mobility threshold for joint detection seems reasonable (estimation of mobility).

C. *Scaling Network Bandwidth*

A base station may transmit its frequency domain samples to different multicast groups for different frequency subbands. The station knows its own available network bandwidth, and it knows the other base stations of the area where cooperation is possible (distances in CP length). A station requests samples of other stations if it has available bandwidth. If it has no bandwidth available, it does not accept sample requests by other stations. Current base station receivers estimate receive SINR values as part of their normal operation (channel estimation). If SINR for a terminal is bad, the base station requests samples from a neighbouring station to improve the SINR by joint detection. If mobility of the terminal is too high, joint detection is not used because the joint channel estimation would perform bad. Cooperation is therefore first done on subbands for critical cell-edge users with low mobility. This control mechanism perform joining and leaving multicast groups dynamically and autoconfiguring, and with the SINR and mobility thresholds scales according to the available network bandwidth and computing power.

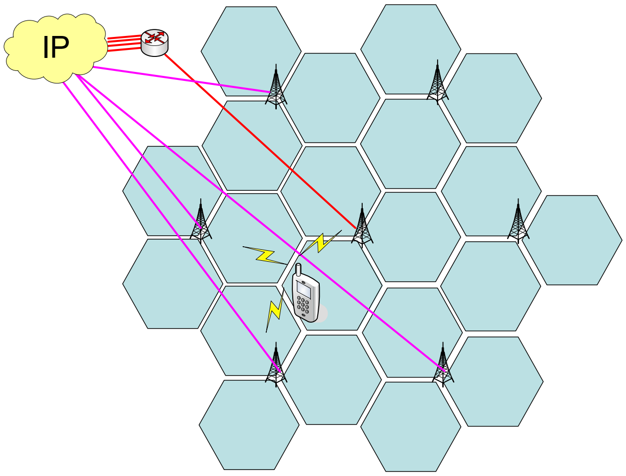

Fig. 4. Cooperative joint detection with one ring of base stations. The station in the middle multicasts receive samples of the frequency subband where the terminal is scheduled in to stations that joined the group. Other stations also multicast received samples, areas of joint processing overlap.

D. *Consequences for Base Station Software*

In addition to the current stack, base stations need a sample server and sample client implementation. The server handles registering for reception of samples of a frequency subband and provides information about the multicast group. Also needed are the protocol for requesting samples and the protocol for sample exchange.

Base stations must be able to stream received samples, and their signal processing must be able to compute larger matrices (including the remote samples)

The described features would be an extension of the protocols running over the X2 interface and might become part of the RRC implementation.

IV. EVALUATION

The multi-cell simulation environment is based on the 3GPP SCME channel model [8]. A scenario mix is used where different base stations may experience line of sight (LOS) or non line of sight (NLOS) channels to the terminal. Interference values are computed for downlink, duality between downlink and uplink is assumed. Parameters are listed in the table I.

The simulated scenario is shown with sector numbering in figure 5. The position of the terminal for evaluation is marked in red. Average receive power levels from all sectors are shown in figure 5. For evaluation, cooperation is always assumed to be done between the three sectors with strongest

TABLE I
SIMULATION PARAMETERS.

Parameter	Value
Channel Model	3GPP SCME
Scenario	Urban-macro
Additional modifications	Scenario mix
f_c	2 GHz
Intersite distance	500 m
Number of Base Stations	19 with 3 sectors each
Number of Mobile Station	1
Base Station height	32 m
Mobile Station height	2 m
Mobility	Pedestrian
Transceiver	SISO
Transmission	Downlink

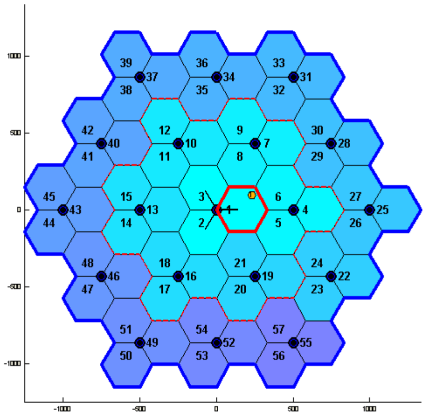

Fig. 5. Sector numbering for dynamic cooperation simulation in hexagonal grid.

receive power levels. Channel estimation errors and other errors are disregarded.

Figure 7 shows three cumulative distribution functions of SIR: the blue curve is without cooperation. The green curve would result from perfect handoff without cooperation: the terminal would always be connected to the sector with strongest receive power. Dynamic cooperation of the three sectors with strongest received power yields the black curve. It can be seen that the described cooperation would yield an improvement of around 20 dB compared to no cooperation.

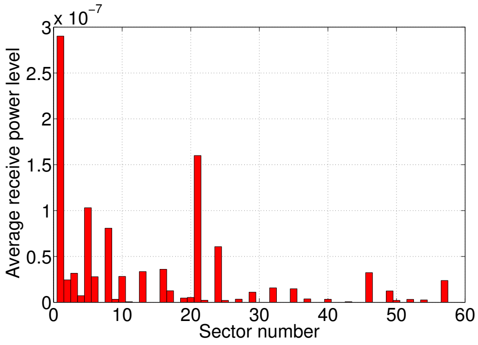

Fig. 6. Average receive power from each base station.

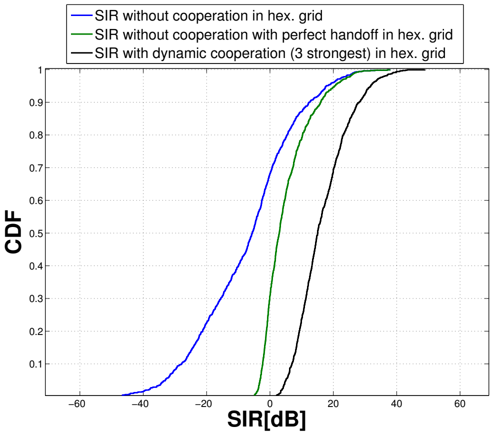

Fig. 7. Cumulative distribution functions of SINR.

V. CONCLUSION

An architecture for joint detection in MIMO-OFDM cellular networks has been presented, taking LTE as example. Main part of the architecture is an efficient protocol for network layer information exchange between cooperating base stations. Base stations adaptively multicast received samples to different groups of neighbouring base stations for different frequency subbands. Computation (joint detection) in this architecture is partly redundant, because there is no actual central unit. Overlapping areas of joint detection are provided, where each base station is a virtual central unit. SINR and mobility thresholds are used to first cooperate for critical cell-edge users with low mobility. The architecture is scaleable in terms of network bandwidth (heterogeneous backhaul) and computational power. Groups of cooperating stations are dynamically selected according to the actual interference situation.

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