Cooperation between Base Stations in Uplink for Future Cellular Networks

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***Abstract*—Nowadays cellular systems operate with frequency reuse one, where adjacent cells use the same frequency band. User Equipments (UEs) located at cell edge are most affected by the resulting co-channel interference. In addition, cell edge UEs suffer from their weak carrier signal strength.**

This paper investigates new methods to increase the performance of cell edge UEs by means of information exchange between Base Stations (BSs). A BS serving a cell edge UE requests support from a co-channel BS. The supporting BS transfers IQ samples, demodulated or decoded bits received from the cell edge UE back to the serving BS. The serving BS then combines the information.

The concept of cooperative BSs developed in this paper is based on a request-response mechanism and does not require a central control node. Performance evaluation by means of simulation shows the capability of BS cooperation applied to the 3GPP Long-Term Evolution (LTE) system in terms of user throughput and emphasizes the trade-off in terms of increased backhaul requirement due to BS-BS communication.

I. INTRODUCTION

In cellular systems with tight frequency reuse, UEs located in nearby co-channel cells can be scheduled on the same physical resources. Their simultaneous transmissions create co-channel interference which reduces Signal to Interference plus Noise Ratio (SINR) and therefore limits capacity.

In conventional cellular systems, co-channel interference is reduced by radio resource management such as power control, loose frequency reuse, spreading code assignments, and inter-cell interference coordination. Uplink (UL) co-channel interference can also be mitigated at the BS receiver by means of multi-antenna processing, e.g., Interference Rejection Combining (IRC) receivers. Performance of multi-antenna reception algorithms is usually limited by the small numbers of Rx antennas at a BS. Leveraging antennas of several cells allows multi-user detection across cell borders leading to improved link quality. Such cooperation across cells is most often modeled as a single super-BS with numerous antennas and central control [1], [2]. In the present paper, a request-response mechanism enables BSs to cooperate on-demand for certain UEs, during certain time slots, and on certain resource blocks (RBs) in a distributed way. Therefore, the developed UL cooperation between BSs can be integrated in the 3GPP logical LTE/SAE architecture. Based on the structure of the LTE physical layer, three different kinds of information exchange can be considered [3], [4]. In the proposed methods, cooperating BSs receive, demodulate or even decode the signal sent by a UE associated to a nearby co-channel cell. The received signal (IQ samples), the demodulated signal (coded bits) or the decoded signal (uncoded bits) is transferred to the serving BS, which combines that information with its own received signal. This paper emphasizes the benefit of BS cooperation for cell edge UEs but also its impact on the traffic volume through the BS-BS interface.

In section II, the main features of LTE are briefly described. Section III introduces the concept of UL cooperation applied to LTE and the different cooperation modes. Section V discusses some Base Station (BS) algorithms affected by cooperation, whereas section IV focusses on the integration of BS cooperation into the conventional cellular system architecture. Finally, some performance results are provided in section VI and section VII concludes the paper.

II. 3GPP LONG-TERM EVOLUTION

A. *LTE physical layer*

LTE can be used in both paired Frequency Division Duplex (FDD) and unpaired Time Division Duplex (TDD) spectrum. It supports flexible carrier bandwidths from below 5 MHz up to 20 MHz. Advanced multi antenna solutions are the key component of LTE. Different advanced multi antenna techniques addresses different scenario. For instance, high peak data rates can be achieved in high SINR regions with multi-layer transmissions while diversity coding or beamforming improves coverage and capacity in low SINR regions.

LTE uses Orthogonal Frequency Division Multiplex (OFDM) for the downlink. OFDM enables a flexible spectrum allocation and cost-efficient solutions for very wide carriers. In OFDM the broad carrier bandwidth is divided in a large number of narrow subcarriers that are modulated individually. OFDM symbols constitute the resource granularity in time while subcarriers represent the granularity in the frequency domain. The basic LTE downlink physical resource can be seen as a time-frequency grid which allows for a channel-dependent resource allocation in time and frequency. The smallest resource unit that can be assigned to a UE is called a Resource Block (RB) and is composed of 14 OFDM symbols and 12 subcarriers.

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In uplink, LTE uses a pre-coded version of OFDM called Single Carrier FDMA (SC-FDMA), which groups allocated resources and pre-codes them with a Discrete Fourier Transform (DFT). The resulting transmission has Single Carrier (SC)-like characteristics.

B. *LTE radio protocols*

The Medium Access Control (MAC) layer performs multiplexing, Hybrid ARQ (HARQ), and scheduling. The scheduler entity of an eNodeB allocates uplink and downlink resources while the entity in the User Equipment (UE) just acts according to the assigned grants. Besides requesting payload of a certain size from the RLC protocol, MAC scheduling controls HARQ retransmissions and it adapts modulation schemes and coding rates.

Radio Link Control (RLC) is responsible for segmentation and/or concatenation of RLC SDUs (header compressed IP packets) into RLC PDUs. The size of the RLC PDUs is controlled by the MAC scheduler. The receiving RLC entity performs the reverse concatenation and/or segmentation operations. Furthermore, RLC provides an error-free, in-sequence delivery of data. The ARQ mechanism handles retransmissions of erroneously received PDUs based on the sequence number. It removes duplicates and re-orders RLC SDUs if necessary.

As the interface towards the Internet Protocol (IP) protocol, Packet Data Convergence Protocol (PDCP) performs IP header compression and it protects the transmitted data by means of ciphering. At the receiver side, PDCP performs the corresponding deciphering and decompression operations.

III. UL COOPERATION BETWEEN BASE STATIONS

According to the regular LTE operation, each UE is associated to one serving BS. The serving BS controls the UEs' transmission parameters, e.g., resource allocation, Modulation and Coding Scheme (MCS) etc. The proposed scheme of BS cooperation enables the serving BS to request cooperation from one or more supporting BSs for selected UEs. Receive signal quality of supported UEs is therefore improved. The information exchange between cooperating BSs can either be IQ samples, hard (uncoded) bits or soft (coded) bits.

A. *IQ sample exchange*

During scheduling, the BS allocates certain RBs to a UE for UL transmission. The serving BS can then request support from one (or more) neighbor BS for this particular UE. Figure 1 shows the Message Sequence Chart (MSC) in case of cooperation with IQ sample exchange. The serving BS should indicate in its message the RBs on which the supported UE transmits. After receiving the UE signal on the indicated RBs, the supporting BS transfers IQ samples received on its antennas to the serving BS. An IQ sample is the complex representation of a constellation point of a given subcarrier received on a given antenna. It is the output of the Fast Fourier Transform (FFT) at the OFDM receiver chain. When the serving BS has received the cooperation response from the supporting BS containing IQ samples, it can jointly process the received signals of all antennas.

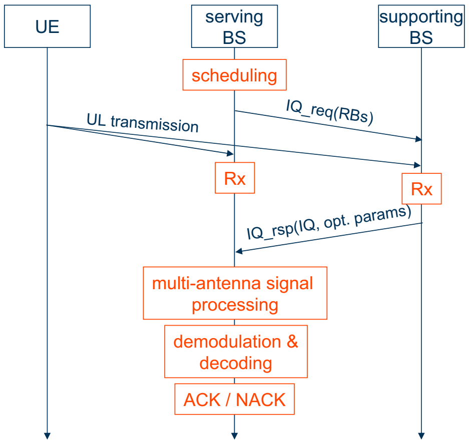

Fig. 1. Message sequence chart for requesting IQ samples from a supporting BS

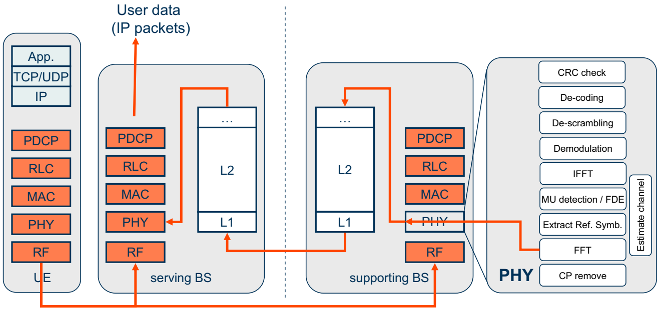

Fig. 2. User plane protocol stack of cooperating LTE BSs

Figure 1 shows that there is no need for a dedicated control node. Whenever the serving BS requires support, it requests it from one or more BS of choice. There are several ways to select an appropriate supporting BS. It can be based on location, on pathloss (long-term channel statistics) or on actual channel realization (short-term), see section V-A.

An example LTE user plane protocol stack of cooperating BSs is shown in Figure 2. The right hand side of the figure focuses on the LTE BS Physical Layer (PHY) layer. The supporting BS extracts the IQ samples of the indicated RBs from its FFT module and transfers them to the serving BS via the BS-BS interface. This BS-BS interface can be any interface that fulfils the capacity and delay requirements, see sections V-C and VI-C. The serving BS exploits the IQ samples in its own PHY layer. Thereby the serving BS's PHY layer virtually increases the number of antenna elements on which the receiver can perform signal processing. Assuming both BSs have four antenna elements each, signal processing is as powerful as if the serving BS had eight antennas.

B. *Coded bit exchange*

The serving BS may request coded bits of the received UE signal. Those are typically quantized (coded) soft bits which are output of the demodulator in the physical layer. The request message contains additional transmit (Tx) parameters compared to Figure 1, such as modulation scheme. The supporting BS has first to detect the Rx signal of the supported UE. When the supporting BS receives a transmission of a UE in its own cell in parallel to the supported UE, it needs to perform multi-user detection. It can apply receiver algorithms that mitigate interference, e.g. IRC [5].

After detection, the serving BS demodulates the signal and generates soft coded bits. It then transfers the quantized coded bits back to the serving BS, which combines the coded bits of the supporting BS with its own coded bits. Chase combining, which is a known scheme to combine HARQ retransmissions can be applied. Finally, decoding takes place at the serving BS.

C. Uncoded bit exchange

In order to reduce the backhaul requirement, the serving BS can request hard (uncoded) bits from a supporting BS. Basically a request-response message exchange similar to Figure 1 takes place. As additional parameter, the request message contains the modulation and coding scheme used by the UE and its specific reference symbols. The supporting BS detects, demodulates and decodes the signal. If the signal is correctly decoded, i.e. when the CRC is successful, the supporting BS transfers the decoded data back to the serving BS. After receiving the response message, the serving BS performs selection combining: the serving BS uses the uncoded bits sent by the supporting BSs when it cannot decode the data itself.

IV. INTEGRATION OF COOPERATION INTO LTE/SAE LOGICAL ARCHITECTURE

3GPP's core network (named System Architecture Evolution (SAE)) and the radio access (named Long-Term Evolution (LTE)) are evolving in parallel [5]–[7]. The resulting flat architecture is composed of only two logical nodes in the User Plane (UP): the eNodeB and the Serving Gateway (S-GW), see Figure 3. The S-GW executes packet filtering, classification and it provides the connection to the Internet or to Public Land Mobile Network. An eNodeB provides the LTE radio access. Like in the UP, only two nodes are involved in the Control Plane (CP): the eNodeB and the Mobility Management Entity (MME). The MME handles core network control functions, such as attach/detach handling, mobility functions, bearer management, and security. eNodeBs are connected to the core network using the IP-based interface S1. The logical interface between eNodeBs, i.e., the IP-based X2 interface supports loss-less mobility and multi-cell Radio Resource Management (RRM).

The distributed approach of BS cooperation in UL can be smoothly integrated in the SAE logical architecture. Indeed, even if the UE signal is received at antennas of different BSs, the serving BS is still in charge of controlling transmission of its UEs as in the conventional case. From the core network perspective the serving BS remains the point of contact for both user and control plane. From a UE perspective UL cooperation is transparent, meaning that UEs are not aware whether they are served cooperatively or not.

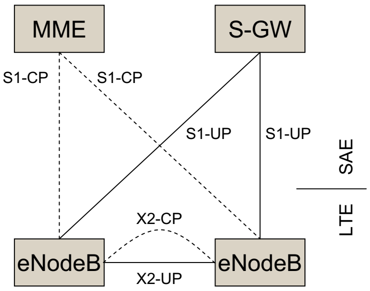

Fig. 3. LTE/SAE logical architecture

V. ALGORITHMS AFFECTED BY BS COOPERATION

A. Selection of supporting BSs

The choice of supporting BSs highly impacts performance. For example in the uncoded bit exchange mode, a remote supporting BS receiving signal from a supported UE with low power will not be able to decode its signal. To explore the potential of BS cooperation, it is basically more appropriate to select supporting BSs whose signals are received with comparable strength as the serving BS signal at the supported UE. Cell edge UEs usually carry out and report signal strength measurements for mobility purposes. These reports can be used by the serving BS to select a set of potential supporting BSs that will receive a cooperation request. However, the supporting BS can reject some cooperation requests. Indeed, for both coded and uncoded bit exchange modes, the number of co-channel UEs supported by a BS should be limited by the number of BS Rx antennas to ensure an efficient multi-user detection. This limitation does not apply to the IQ sample exchange mode, in which the supporting BS does not detect signal of the supported UEs. Nevertheless, in cases with limited BS-BS interface capacity there still will be restrictions on the number of supporting BSs per UE and the amount of UEs that can be supported by a BS.

B. Link adaptation

Link adaptation is necessary to overcome varying channel conditions and interference levels. The MCS and the Tx power of an UL transmission is adapted to the SINR experienced at the BS. A robust MCS and a high Tx power can cope with unfavorable channel conditions. If the Rx signal quality is good, the Tx power can be decreased to reduce interference caused to co-channel UEs and/or a more aggressive MCS can be used to improve the achieved throughput. BS cooperation increases UL Rx signal quality by leveraging the multiple channels from the UE to a plurality of BSs. The improved Rx signal quality can be used as input to the MCS and Tx power selection algorithm.

C. HARQ mechanisms

In the LTE HARQ mechanism, an acknowledgement (ACK) or a non-Acknowledgment (NACK) feedback is sent four

Transmission Time Intervals (TTIs) after receiving a packet. In case of BS cooperation the serving BS can not transmit a reasonable ACK/NACK feedback before it has received and combined the IQ samples, coded or uncoded bits from the supporting BSs with its own signal. Thus, either the process of BS cooperation including signal processing and information exchange can be finished in time or the HARQ mechanism has to be adapted to allow for longer feedback delays.

VI. PERFORMANCE EVALUATION

A. Simulation environment

The behavior of cooperative BSs has been implemented in a multi-cell radio network simulator modeling OFDM transmission with multi-antenna transmitters and receivers.

In the following, BS cooperation is evaluated in a fully loaded 10 MHz FDD LTE network which consists of 7 sites with three sectors (cells) per site. The inter-site distance is 500 m. Each cell has 10 users in average and operates at a carrier frequency of 2 GHz. Each BS has four antennas and applies Interference Rejection Combining (IRC) receiver. The evaluation assumptions are essentially based on the Next Generation Mobile Networks (NGMN) recommendations [8]. The channel model used for evaluation is the urban scenario outlined in [9] with a user velocity of 3km/h.

In each cell, a channel dependent scheduler allocates equal number of RBs to users according to their experienced channel conditions. Channel quality is measured on the sounding signal which is transmitted every 20ms.

A conventional open loop power control, which is not adapted to BS cooperation, is applied [5]. Link adaptation allows QPSK, 16QAM, and 64QAM modulation schemes. Turbo coding with adaptive rate matching allows for various combinations of Modulation and Coding Schemes (MCSs). The increased SINR due to BS cooperation is computed in every TTI and is used for link adaptation after a processing delay of another TTI (1ms). A link-to-system interface based on mutual information maps the packet SINR to the corresponding Block Error Ratio (BLER) [10]. The extra delay introduced by BS cooperation is assumed to be low enough so that HARQ feedback can be send in time.

In the following, we use the expression *cooperating* or *supporting cell* meaning that the BS in charge of the particular cell cooperates by providing the requested information (IQ samples, coded or uncoded bits) of the corresponding antennas. For instance, when cooperation is restricted to a maximum of 3 supporting cells, than the UE signal is received in up to 4 different cells by 16 different antennas. Another parameter named *cooperation range* determines which UEs will be served under cooperation. Only UEs measuring a signal strength of co-channel BS within a certain cooperation range below the signal strength of the serving BS are chosen for cooperation. In the following the impact of the maximum number of supporting cells per UE and the cooperation range on performance is studied.

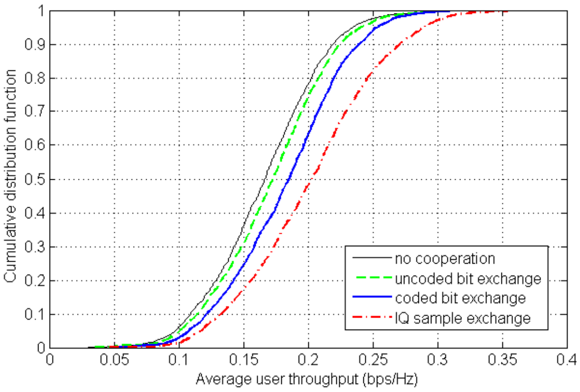

Fig. 4. CDF of average user throughput for different cooperation modes (max. of 2 supporting cells, 10dB cooperation range)

B. Performance evaluation

Figure 4 shows the Cumulative Distribution Function (CDF) of the average user data rate for the 3 different cooperation modes: IQ sample, coded bit, and uncoded bit exchange. The gain obtained with IQ sample exchange exceeds the one obtained with coded bit exchange, which in turn outperforms the uncoded bit exchange mode. At 10 dB range and with a maximum of 2 supporting cells, the cell edge data rate (represented by the CDF 5%-tile point) increases by 3.06% for uncoded bit exchange, 10.2% for coded bit exchange and 21.43% for IQ sample exchange compared to the conventional system without cooperation, see Table I. By combining coded bits received from supporting cells with its own coded bits, the serving BS aggregates the information of the UE signal received through several channels. In the uncoded bit exchange mode, the serving BS can only select between using uncoded bits from the supporting cell or using its own uncoded bits, which explains the moderate gains it provides. In case of IQ sample exchange, the serving BS virtually increases its number of Rx antennas, enabling more efficient interference mitigation and a higher carrier strength.

It can be seen in Figure 4 that not only the 5%-tile point but also the whole CDF curve is improved with cooperation. In fact it is possible that some supported UEs exceed performance of certain non-supported UEs due to BS cooperation. ~~In that case, the performance of cooperation can not be exactly measured with the 5%-tile point shifting.~~ Figure 5 shows the actual throughput increase of supported ~~users~~ due to cooperation. With IQ sample exchange, throughput of supported UEs rises by 35.6% in average. For the coded bit exchange mode the increase in supported user throughput reaches 17.8%, whereas it reduces to 4% when cooperation is based on uncoded bit exchange.

Due to BS cooperation, more information on the Rx signal is acquired at the BS receiver resulting in a SINR increase. Figure 6 shows the CDF of the SINR increase for different cooperation modes. BS cooperation based on IQ sample exchange enables the BS receiver to use information

TABLE I
AVERAGE CELL THROUGHPUT AND 5%-PERCENTILE USER THROUGHPUT FOR DIFFERENT COOPERATION MODES

	Av. cell throughput		5%-percentile user throughput	
	$\left[{}^{bps}/_{Hz}\right]$	[%]	$\left[{}^{bps}/_{Hz}\right]$	[%]
No cooperation	1.66		0.098	
Uncoded bit exchange	1.7	+2.41	0.101	+3.06
Coded bit exchange	1.82	+9.64	0.108	+10.2
IQ sample exchange	2.01	+21.08	0.119	+21.43

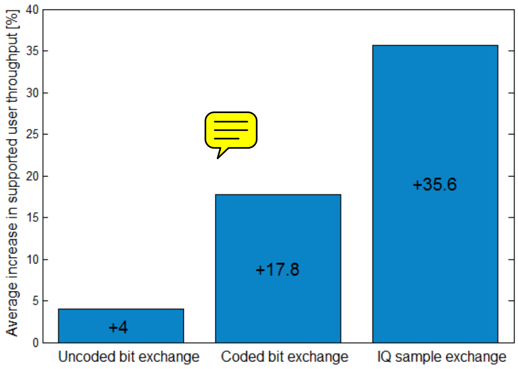

Fig. 5. Average throughput increase of users with 1 and 2 supporting cells

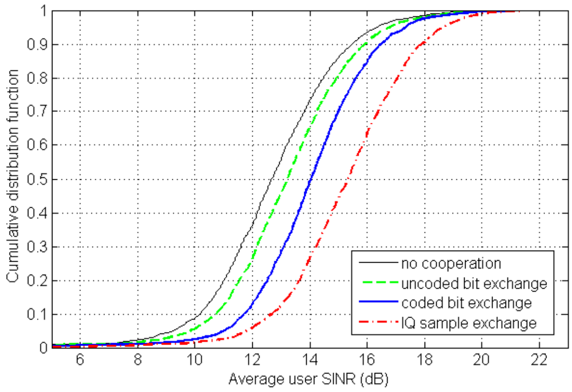

Fig. 6. CDF of average SINR per UE for different cooperation modes (max. of 2 supporting cells, cooperation range of 10dB)

received by antennas of supporting cells as if they were its own antennas. The SINR increase comes from multi-antenna receiver algorithms and reaches 2.5dB in average for the considered scenario. In case of the coded bit exchange mode the observed average SINR increase of 1.3dB in Figure 6 comes from Chase combining between coded bits from serving cell and supporting cells. For the uncoded bit exchange mode, the SINR rises moderately (0.5dB in average) because the serving BS can only select between using uncoded bits from supporting cells or using its own uncoded bits. However, it can store the maximum between the SINR seen from supporting cells and the SINR seen by itself and use it as input to link adaptation algorithms.

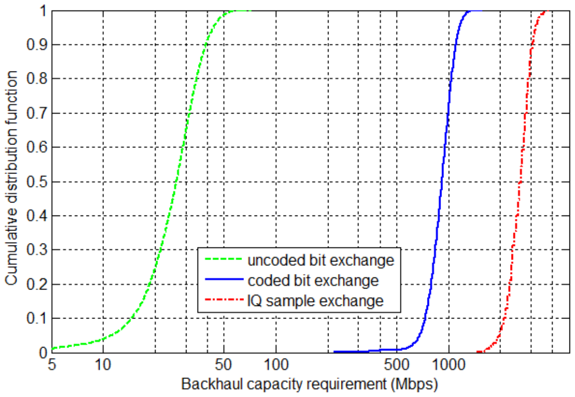

Fig. 7. CDF of backhaul capacity requirement per site for different cooperation modes (max. of 2 supporting cells, cooperation range of 10dB)

TABLE II
REQUIRED BACKHAUL CAPACITY PER INCREASED CELL THROUGHPUT

Cooperation mode	Required backhaul capacity [Mbps] for 1% increase in cell throughput
Uncoded bit exchange	11.2
Coded bit exchange	95.4
IQ sample exchange	123.3

C. *Backhaul requirement*

Cooperation requires information exchange between cells located at different sites. By means of system level simulations, the required backhaul capacity per site is measured as the sum of the input and output traffic generated by one three-sectored BS due to the exchange of IQ samples, coded or uncoded bits. Information exchange between cells of the same site is neglected. For the following evaluation one IQ sample is assumed to be quantized with 16 bits while one soft value of a coded bit is represented by 5 bits. Figure 7 shows the resulting backhaul capacity requirement per site for the three different cooperation modes.

~~Cooperating~~ based on uncoded bit exchange results in an average backhaul traffic of 27 Mbps. The coded bit exchange mode and IQ sample mode, which show larger gain in user data rate, require higher average backhaul capacity of 920 Mbps, respectively 2.6 Gbps. As expected there is a tradeoff between (cell edge) user throughput improvement and backhaul capacity requirement. A new metric quantifies the backhaul capacity required to increase the mean cell throughput by 1%. Table II shows that exchanging uncoded bits is more efficient from a backhaul perspective. However, exchanging IQ samples is still more promising since it yields higher user throughput gains.

VII. CONCLUSION

Cooperative BSs exchanging IQ samples enables to virtually increase the number of antennas on which a serving BS can apply multi-antenna signal detection. This way, co-channel interference is efficiently mitigated and the received signal strength is also increased. The maximum number of cooperating BSs is however limited by the transmission capability of the BS-BS interface. Performance evaluation by means of simulation showed that BS cooperation based on IQ sample exchange can increase the average cell throughput by 21.08% and the 5%-tile user throughput by 21.43% for a cooperation range of 10dB and a maximum of 2 supporting cells per UE. As a trade-off, the requirement on BS-BS interface capacity increases, too: 2.6 Gbps are required for the information exchange between cells of different site. Other schemes of BS cooperation less demanding in backhaul capacity have been investigated. They are based on uncoded or coded bit exchange. These modes of BS cooperation improve the received signal quality of (cell edge) UEs by leveraging information received at several cells. The average cell throughput goes up by 2.41 and 9.64% for the uncoded and coded bit mode respectively while the 5%-tile user throughput rises between 3.06 and 10.2% for a cooperation range of 10dB and a maximum of 2 supporting cells per UE. These modes have the advantage to generate less traffic on the backhaul: between 27 and 920 Mbps are required for the information exchange between cells for these modes. ~~Finally, BS cooperation can be integrated in the 3GPP logical LTE/SAE architecture. The approach is implicitly backward compatible and can be seen as a potential evolution of cellular systems.~~

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