

Inter-Site Joint Detection with Reduced Backhaul Capacity Requirements for the 3GPP LTE Uplink

Philipp Frank^{*}, Andreas Müller[‡] and Joachim Speidel[‡]

^{*}Deutsche Telekom Laboratories, Berlin, Germany

[‡]Institute of Telecommunications, University of Stuttgart, Germany

E-Mail: philipp.frank@telekom.de

Abstract—Cellular networks operating with a frequency reuse factor of one are often interference-limited. For that reason, base station (BS) cooperation techniques aiming at mitigating the effects of interference caused by simultaneous transmissions on the same frequency resources in nearby sectors may considerably improve the system performance. However, for that purpose generally high-capacity backhaul links are required, which are often not available in practice. A crucial factor for realizing such cooperative techniques in the short-term therefore is to develop efficient ways for reducing the backhaul load without significantly worsening the achievable performance. In this paper, we evaluate the performance of inter-site joint detection with reduced backhaul capacity requirements for the uplink of a 3GPP UTRAN Long Term Evolution (LTE) system, where different BSs cooperate with each other in order to jointly detect the signals transmitted by various users. By means of extensive system-level simulations, we show that with the proposed methods still significant performance gains may be realized over conventional systems—especially in terms of the cell-edge throughput—while the backhaul load can be considerably reduced compared to a system with full-complexity joint detection.

I. INTRODUCTION

The main factor limiting the performance of current cellular networks, such as the 3GPP UTRAN Long Term Evolution (LTE), is other sector interference as the transmission in one sector is perceived as interference by other sectors nearby. Therefore, techniques for combating other sector interference recently have attracted a lot of research attention, including amongst others static and dynamic interference coordination [1] as well as coordinated multipoint (CoMP) transmission and reception [2]–[4]. In contrast to static interference coordination based on fractional frequency reuse, where the resource allocation of the user equipments (UEs) is restricted to certain parts of the available bandwidth depending on whether they are located at the cell-center or at the cell-edge, more sophisticated and spectrally-efficient techniques will play a crucial role for next generation cellular networks, because of their potential for providing significantly higher spectral efficiencies. One of these promising techniques is CoMP transmission/reception, where different base stations (BSs) cooperate with each other via a fast backhaul network in order to virtually establish a distributed antenna array among all antennas of the cooperating BSs. This way, multiple cooperating BSs are able to jointly transmit to one or multiple UEs in the downlink or to jointly detect the received signals in the uplink in order to improve the signal detection. In contrast to intra-site

cooperation [5], where only sectors belonging to the same BS site may cooperate, employing inter-site cooperation is more involved due to several practical constraints, such as the additional delay due to the information exchange between the cooperating BSs and the joint processing, the synchronization of the UEs to all cooperating BSs as well as the adjustment of the timing advance. One of the main challenges for realizing inter-site cooperation in practical systems, however, is the tremendous amount of data to be exchanged between the cooperating sectors of different BS sites.

A first system-level analysis of uplink inter-site joint detection has been presented in [4]. In this paper, we propose beyond that two different methods for restricting inter-site cooperation to certain frequency resources in order to ease the backhaul capacity requirements without significantly degrading the achievable performance. For this purpose, we only allow inter-site cooperation either for a fixed subcarrier pattern or for certain physical resource blocks (PRBs) selected based on a predefined signal-to-noise-plus-interference ratio (SINR) threshold. Furthermore, we thoroughly evaluate the system performance of both methods for the LTE uplink and compare it to a full-complexity joint detection system as well as to a conventional system without any cooperation.

The remainder of this paper is organized as follows: In Section II, we first of all describe the considered inter-site cooperation scheme in detail. Afterwards, we present our proposed backhaul load reduction methods in Section III, followed by our simulation methodology in Section IV. Finally, some system-level simulation results are discussed in Section V and our conclusions are given in Section VI.

II. INTER-SITE JOINT DETECTION

We consider the uplink of a cellular network as depicted in Fig. 1 (b), where different BS sites are interconnected with each other via high-capacity backhaul links, thus facilitating a fast information exchange between them. In case of a 3GPP LTE system as considered here, this data exchange could be realized by means of the X2 interface, for example [6]. Hence, not only intra-site cooperation according to Fig. 1 (a) may be performed, i.e., that the sectors of the same BS site may cooperate with each other, but also inter-site cooperation across sectors belonging to different sites. Possible cooperation clusters for the exemplary UE indicated in Fig. 1 are for both cases illustrated by means of the shaded areas. The proposed

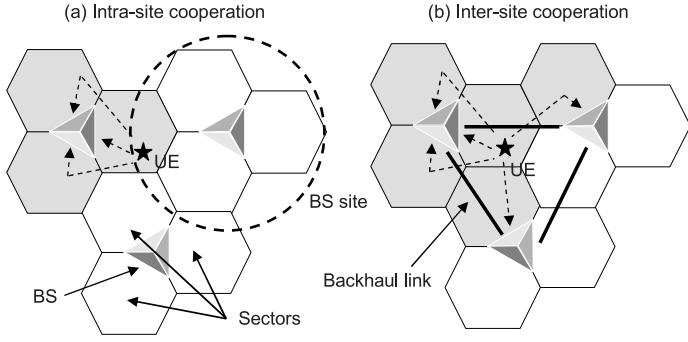


Fig. 1. Comparison between intra-site cooperation and inter-site cooperation.

inter-site cooperation scheme is based on a decentralized cooperation concept, where the particular cooperation clusters may be different for different UEs and depend—among other things—on the received signal strengths at the various UEs, as will be outlined in more detail below.

In the following, we always assume that all UEs are equipped with a single antenna element only and that each BS site is made up of K different sectors with N different antenna elements per sector. As in conventional systems without any cooperation, every sector always performs independent scheduling and assigns certain PRBs as well as appropriate transmit power levels to the various UEs. After having signaled the scheduling grants over the air, each sector may request support for its currently scheduled UE from the sectors belonging to the respective cooperation cluster in order to virtually increase the number of receive antennas, thus improving the signal detection. After the actual uplink transmission, the i -th sector of a certain BS site receives on a single subcarrier the baseband signal \mathbf{r}_i given by¹

$$\mathbf{r}_i = \mathbf{h}_{i,l} s_l + \sum_{j \in \mathbb{M}_{i,l}} \mathbf{h}_{i,j} s_j + \mathbf{i}_i + \mathbf{n}_i, \quad l \in \mathbb{G}_i \quad (1)$$

with \mathbb{G}_i as the set of UEs associated to the i -th sector, $\mathbb{M}_{i,l}$ as the set of cooperating sectors associated with the scheduled UE l in the i -th sector, $\mathbf{h}_{i,j}$ as the N -dimensional channel vector from the currently scheduled UE in the j -th sector to the antenna elements of the i -th sector, s_j as the symbol transmitted by the currently scheduled UE in the j -th sector, and \mathbf{i}_i as well as \mathbf{n}_i as the other sector interference and thermal noise, respectively. By combining the signals received by all cooperating sectors, we actually obtain a virtual multiple-input multiple-output (MIMO) system, what we illustrate in the following for notational convenience for the particular case with $K = 3$, where sector 1 receives the signal transmitted by UE 1, and where the cooperation cluster for UE 1 consists of the sectors 2 to 5. In this case, the resulting effective received

¹In contrast to orthogonal frequency division multiple access (OFDMA) used for the LTE Release 8 downlink, where a data symbol is exactly mapped on a certain subcarrier, L different data symbols are spread onto L subcarriers in case of single-carrier frequency division multiple access (SC-FDMA) for the LTE Release 8 uplink. As a result, s_l in (1) contains contributions of all L data symbols transmitted by the respective UE.

signal $\mathbf{y}_1 = [\mathbf{r}_1^T \cdots \mathbf{r}_5^T]^T$ determined by sector 1, with $(\cdot)^T$ as the transpose operator, can be written as

$$\mathbf{y}_1 = \underbrace{\begin{bmatrix} \mathbf{h}_{1,1} & \cdots & \mathbf{h}_{1,5} \\ \vdots & \ddots & \vdots \\ \mathbf{h}_{5,1} & \cdots & \mathbf{h}_{5,5} \end{bmatrix}}_{\mathbf{H}} \underbrace{\begin{bmatrix} s_1 \\ \vdots \\ s_5 \end{bmatrix}}_{\mathbf{s}} + \underbrace{\begin{bmatrix} \mathbf{i}_1 \\ \vdots \\ \mathbf{i}_5 \end{bmatrix}}_{\mathbf{i}} + \underbrace{\begin{bmatrix} \mathbf{n}_1 \\ \vdots \\ \mathbf{n}_5 \end{bmatrix}}_{\mathbf{n}}. \quad (2)$$

Clearly, sector 1 may then easily detect the transmitted signal from the associated UE 1 as well as from the UEs 2 to 5 located within the cooperating sectors by using a standard MIMO receiver [5], provided that reasonably accurate channel state information (CSI) from all these UEs is available. However, each sector only evaluates the symbol transmitted by its scheduled UE because this way the cooperation delay is not further increased by the exchange of the detected symbols between different BS sites. Please note that each sector has to provide its own multi-cell CSI to any of the cooperating sectors, so that each of them is able to determine the overall channel matrix \mathbf{H} , which in turn is required for the demodulation of the transmitted signals as well as for the link adaptation. For the latter case, i.e., the selection of an adequate modulation and coding scheme (MCS) subject to a certain block error rate (BLER) constraint, it is taken into account that afterwards joint detection will be performed. In particular, the link adaptation is performed based on the estimated SINR that is obtained by evaluating all signals received by all cooperating BSs, thus usually resulting in the selection of a spectrally more efficient MCS than in conventional non-cooperative systems. For that purpose, each sector periodically provides both scheduling information as well as multi-cell CSI to the sectors within the cooperation cluster. The scheduling information is required for selecting the appropriate CSI of the currently scheduled UEs located within the cooperation cluster in order to determine the SINR expected with joint detection.

The selection of an appropriate cooperation cluster is based on so-called reference signal received power (RSRP) measurements [7], which are normally used for handover decisions in conventional LTE systems. In fact, the UEs rank different sectors according to their signal strength and report this information back to their respective serving BSs. Without loss of generality, let us denote Ψ_k as the ordered set of inter-site sectors, which can be perceived by the UE with index k , where the ordering is done in such a way that the corresponding RSRPs are non-increasing. Then, the i -th inter-site sector is incorporated into the cooperation cluster if the maximum number of cooperating sectors is not yet reached and if the following condition is met

$$P_{\text{serv},k} - \Psi_k(i) < \eta \quad \text{for } i = 1, \dots, |\Psi_k|, \quad (3)$$

with $|\cdot|$ as the cardinal number operator, $P_{\text{serv},k}$ as the RSRP from the serving BS, and η as the cooperation threshold. As a result, the cooperation cluster obviously may be different for each UE and the larger the cooperation threshold η in (3), the more UEs benefit from joint detection.

III. BACKHAUL LOAD REDUCTION

In the following, we propose two different methods for further reducing the backhaul capacity requirements. As already mentioned before, the data to be exchanged within a cooperation cluster generally comprises baseband signals for the relevant subcarriers, scheduling information as well as instantaneous CSI of each cooperating sector determined by multi-cell channel estimation. However, in addition to that, also knowledge about the sounding reference signals and hopping sequences assigned to the various UEs in all cooperating sectors is required in order to be able to perform accurate multi-cell channel estimation. Hence, this information additionally would have to be exchanged between the cooperating sectors, but since the assigned sounding and hopping sequences in general do not change during every TTI, this should cause only minor extra backhaul traffic.

As the exchange of the baseband signals constitutes a significant fraction of the overall backhaul traffic, the basic idea of our approaches is to reduce the inter-site cooperation either to a preselected subcarrier pattern or to those PRBs, on which high interference might occur. In the latter case, every sector only requests additional support from cooperating inter-site sectors for a certain PRB if the instantaneous SINR averaged over the subcarriers belonging to that PRB is smaller than a predefined SINR threshold γ , i.e., if

$$\frac{1}{Q} \sum_{q=1}^Q \frac{E_{s_q} \mathbf{w}_q \mathbf{h}_q \mathbf{h}_q^\dagger \mathbf{w}_q^\dagger}{\mathbf{w}_q \text{diag} \left(\mathbb{E} \left[\mathbf{i}_q \mathbf{i}_q^\dagger \right] + \mathbb{E} \left[\mathbf{n}_q \mathbf{n}_q^\dagger \right] \right) \mathbf{w}_q^\dagger} < \gamma, \quad (4)$$

where Q denotes the number of subcarriers per PRB, E_{s_q} the mean energy per transmit symbol, \mathbf{w}_q the weight vector, \mathbf{h}_q the channel vector, \mathbf{i}_q the interference, \mathbf{n}_q the thermal noise and γ a SINR threshold. Furthermore, $(\cdot)^\dagger$ indicates the conjugate-transpose operator and $\text{diag}(\cdot)$ the diagonalization operator, which sets all elements of a matrix except for its main diagonal equal to zero.

Depending on the actual value of γ , the amount of data to be exchanged consequently can be significantly reduced by performing inter-site cooperation only for PRBs with low SINRs. With our second approach, in contrast, we reduce the required backhaul capacity by exchanging the relevant information not for all subcarriers on which a UE is scheduled, but only for a subset according to a predefined pattern. A simple example would be that only for every second subcarrier a cooperation across different BSs takes places while for the remaining ones only the signals received at the respective serving BS are evaluated. Clearly, both approaches may also be readily combined together in practical systems.

IV. SIMULATION METHODOLOGY

We investigate the performance of the proposed inter-site joint detection scheme with backhaul capacity reduction by means of extensive system-level simulations for a 3GPP LTE Release 8 system. The considered deployment scenario corresponds to a standard hexagonal grid consisting of 19 BS sites with three sectors per site and we apply the wrap

around technique in order to avoid any border effects. Multi-path fading is modeled by means of the 3GPP spatial channel model (SCM) and we make use of the mutual information effective SINR mapping (MIESM) for realizing the link-to-system interface. Moreover, the link adaptation is modeled with a realistic round-trip delay and apart from conventional fast inner-loop link adaptation, we additionally make use of the same outer loop link adaptation scheme as considered in [8] in order to really achieve the desired target block error rate (BLER) on average. The transmit power of all UEs is adjusted based on a simple open-loop scheme as (in dBm)

$$P_{\text{TX}} = \min \{ P_{\text{max}}, P_0 + 10 \log_{10} M + \alpha \text{PL} \}, \quad (5)$$

with P_{max} as the maximum transmit power, P_0 as a reference power, M as the number of assigned PRBs and α as well as PL as a constant path loss compensation factor and the long-term attenuation of the channel between the UE and its serving BS, respectively. Furthermore, the scheduling is always frequency-selective proportional fair according to [9] and retransmissions are processed by means of a synchronous, non-adaptive hybrid automatic repeat request (HARQ) protocol with incremental redundancy. In this regard, we assume that both baseband signal exchange and joint signal processing are completed in time, so that the specified round-trip time for a HARQ protocol process is not exceeded. Otherwise the HARQ timing would have to be adjusted, what however, is not considered in more detail here. Further important system parameters are summarized in Table I.

The system performance evaluations are carried out under the assumption that the different delay spreads of a signal transmitted by a certain UE to the cooperating sectors do not exceed the cyclic prefix length. In general, the UEs have to transmit their signals slightly in advance to ensure that they arrive at their respective serving BS at the expected time due to the propagation delay. Typically, the propagation delays from a certain UE to different sectors are varying significantly, so that the transmitted signal arrives at the serving BS at the expected time after timing advance adjustment, but may arrive to any of the cooperating sectors earlier or later than expected. While improper timing advance adjustment certainly would have only a minor impact on the system performance for small inter-site distances and cooperation cluster sizes, a certain performance degradation is expected in case of large propagation delays. However, by neglecting this issue, we are still able to reveal the fundamental potential of our proposed scheme and leave a more detailed analysis of improper timing advance adjustment for our future work.

V. SIMULATION RESULTS

Fig. 2 shows the system performance for our proposed joint detection scheme with intra-site and inter-site cooperation, respectively. Both the average spectral efficiency and the cell-edge throughput, which is defined as the 5th percentile of the UE throughput distribution, are illustrated and we consider the Macro 1 and Macro 3 cases, respectively. If not stated otherwise, we always assume that at most three inter-site

TABLE I
SYSTEM LEVEL SIMULATION PARAMETERS

Parameter	Setting
Deployment scenario	19 BS sites with 3 sectors per site
Inter-site distance (ISD)	500 m [Macro 1] or 1732 m [Macro 3]
Carrier freq. / bandwidth	2.0 GHz / 10 MHz
Channel model	3GPP SCM
Distance-dependent path loss	According to 3GPP TR 25.814 [10]
Shadowing standard deviation	8 dB
UE speed	3 kmph (quasi-static)
Default number of UEs/sector	10
Target BLER	10%
UE / BS antennas	1 / 2 per sector
Traffic model	Infinite full buffer
HARQ	Synchronous, non-adaptive
Scheduling algorithm	Proportional-fair according to [9]
Link-to-system interface	MIESM
BS antenna spacing	10λ , λ : wavelength
Power control	$P_0 = -58$ dBm, $\alpha = 0.6$ [Macro 1] $P_0 = -60$ dBm, $\alpha = 0.6$ [Macro 3] $P_{\max} = 24$ dBm
BS receiver types	MRC (w/o cooperation), LMMSE (w/ cooperation)
Channel estimation	Ideal
Control channel overhead	Upper and lower 4 PRBs
Reference signals overhead	According to 3GPP TS 36.211 [11]
CSI exchange interval	2 TTIs

sectors per UE can cooperate with each other. Hence, the cooperation cluster in case of inter-site joint detection consists of the two intra-site sectors plus the additional inter-site ones. It can be seen from Fig. 2 that even for a small cooperation threshold significant gains can be achieved with the proposed joint detection scheme, where particularly the cell-edge throughput can be considerably improved. Furthermore, we note from Fig. 2 that the cell-edge performance gains for the Macro 3 case with a relatively large inter-site distance are even higher than those for the Macro 1 case. This can be explained by the fact that in the Macro 3 case most of the other sector interference can be already eliminated with the support of at most three additional inter-site sectors due to the larger inter-site distance in that case. Finally, it should be noted that in case of $\eta = \infty$ not only cell-edge UEs, but also cell-center ones benefit from joint detection. Therefore, the system performance can be even further improved in that case, but this comes at the cost of an increased backhaul load. This is also confirmed by Fig. 3, where the required backhaul capacity as well as the number of cooperating inter-site sectors per UE for various cooperation thresholds are illustrated. For that purpose, we assume a quantization granularity of 30 bits per baseband sample and we measure the required backhaul load as the sum of the occurring input and output traffic at a certain BS site, considering baseband signal, CSI as well as scheduling information exchange². Clearly, the more

²For the calculation of backhaul traffic caused by the exchange of CSI and scheduling information, we assume a quantization granularity of 50 bit per resource allocation table and 16 bit per channel impulse response, 16 pilots per PRB and a CSI exchange interval of two TTIs, leading to a backhaul load requirement per BS for the considered scenario of about 129 Mbit/s and 7 Mbit/s in case of CSI and scheduling information exchange, respectively. Please note that we are not considering any sophisticated quantization methods and leave a more detailed treatment therefore for our future work.

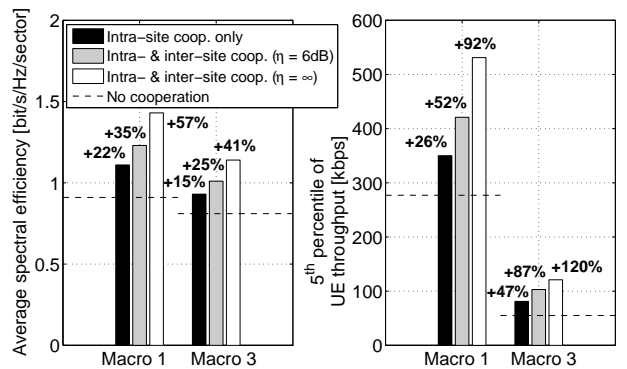


Fig. 2. System performance comparison between various intra- and inter-site cooperation schemes for the Macro 1 and Macro 3 case. The given percentages denote the relative performance gains compared to a conventional system without cooperation.

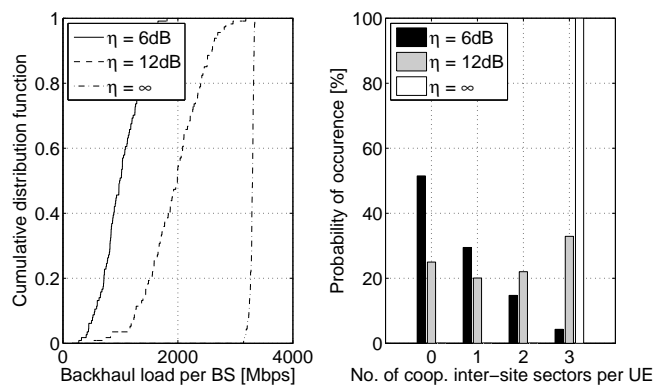


Fig. 3. Backhaul load per BS as well as the number of cooperating inter-site sectors for various cooperation thresholds in case of Macro 1.

UEs and sectors participate in the cooperation, the higher the backhaul requirements get. Fig. 4 shows the impact of the number of cooperating inter-site sectors per UE on the system performance for the Macro 1 and Macro 3 case, respectively. There is no restriction on the number of cooperating inter-site sectors per UE and the cooperation threshold is set to $\eta = \infty$, i.e., all UEs are jointly detected by all sectors within the cooperation cluster. Clearly, the system performance can be improved with increasing number of cooperating sectors since more and more other sector interference is transformed into useful signals this way. However, in the Macro 3 case the performance already saturates for a small number of cooperating sectors because of the relatively large distances between the UEs and the BSs. This reflects that in this case the biggest share of the interference comes from a few surrounding sectors only.

Fig. 5 illustrates the impact of the cooperation threshold η on the system performance for inter-site joint detection combined with the two different backhaul capacity reduction methods outlined before as well as for the conventional case, where the amount of data to be exchanged is not reduced. As can be seen, with increasing number of subcarriers per

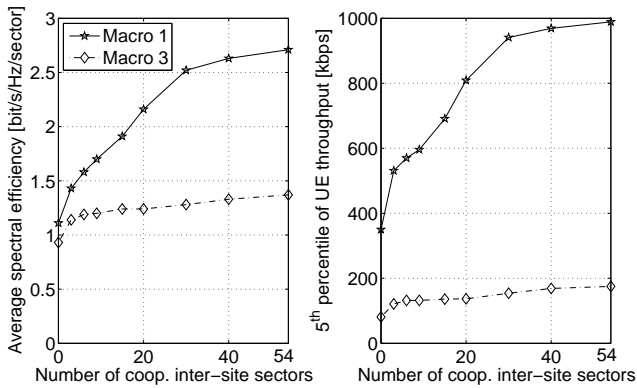


Fig. 4. Impact of the number of cooperating inter-site sectors on the system performance for the Macro 1 and Macro 3 case ($\eta = \infty$).

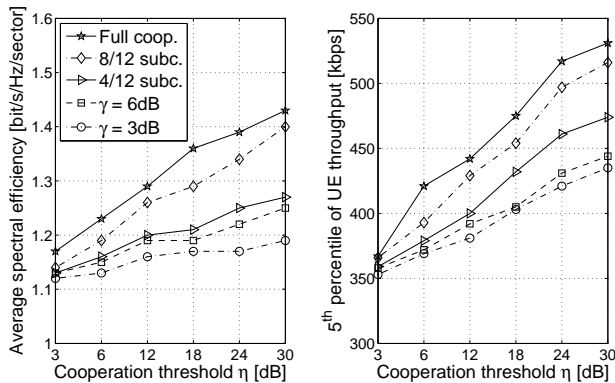


Fig. 5. Impact of the cooperation threshold on the system performance for various cooperation schemes in case of Macro 1

PRB allowed for inter-site cooperation the system performance steadily improves. The upper performance bound, where all subcarriers are considered for inter-site cooperation, can be nearly reached if only 8 of 12 subcarriers per PRB are considered. Furthermore, by comparing the performance of $\gamma = 6$ dB with the subcarrier pattern 4/12 under consideration of the required backhaul load in Fig. 6, we note that the gains of the subcarrier pattern method are slightly higher than the ones of the SINR threshold based method. This is because the interference cannot be accurately determined in advance due to the highly volatile interference situation as from one TTI to the other different UEs might be scheduled in nearby sectors. As a result, often PRBs are selected for inter-site cooperation where additional support of inter-site sectors does not lead to a significant performance improvement. Finally, Fig. 6 depicts the required backhaul load per BS for the proposed backhaul capacity reduction methods and it can be seen that a significant backhaul capacity reduction can be realized with the proposed methods, ranging from 23 % to 66 % on average.

VI. CONCLUSION

We have evaluated the achievable performance of the uplink of a 3GPP LTE system with inter-site joint detection, where

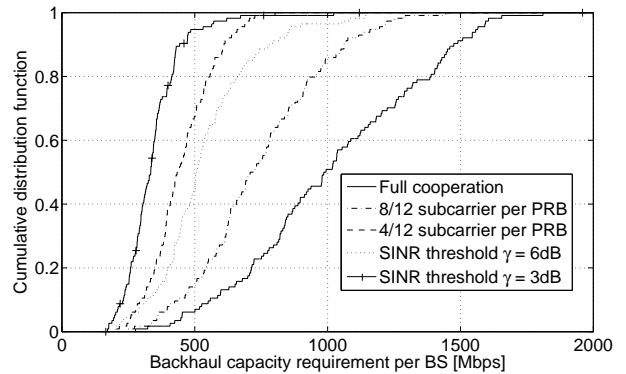


Fig. 6. Cumulative distribution function of the required backhaul capacity for various cooperation schemes in case of Macro 1 and $\eta = 6$ dB.

different sectors belonging to the same or different BS sites may cooperate with each other in order to jointly detect the signals transmitted by the various UEs. Furthermore, we have proposed two novel methods for efficiently reducing the amount of data to be exchanged over the underlying backhaul network and we have shown that with these approaches the backhaul load may be significantly reduced while still achieving a rather good performance.

ACKNOWLEDGMENT

The authors acknowledge the excellent cooperation of all partners within the EASY-C project and the support by the German Federal Ministry of Education and Research (BMBF). We would also like to thank H. Droste (Deutsche Telekom Laboratories) for his helpful suggestions.

REFERENCES

- [1] G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang, and S. Vrzic, "Interference coordination and cancellation for 4G networks," *IEEE Commun. Mag.*, vol. 47, no. 4, pp. 74–81, Apr. 2009.
- [2] M. Karakayali, G. Foschini, and R. Valenzuela, "Network coordination for spectrally efficient communications in cellular systems," *IEEE Wireless Commun.*, vol. 13, no. 4, pp. 56–61, Aug. 2006.
- [3] H. Huang, M. Trivellato, A. Hottinen, M. Shafi, and R. V. P. Smith, "Increasing downlink cellular throughput with limited network MIMO coordination," *IEEE Trans. Wireless Commun.*, vol. 8, no. 6, pp. 2983–2989, Jun. 2009.
- [4] C. Hoymann, L. Falconetti, and R. Gupta, "Distributed uplink signal processing of cooperating base stations based on IQ sample exchange," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2009.
- [5] A. Müller, P. Frank, and J. Speidel, "Performance of the LTE uplink with intra-site joint detection and joint link adaptation," in *Proc. IEEE Veh. Technol. Conf.*, May 2010.
- [6] 3GPP TS 36.420 V8.1.0, "Evolved universal terrestrial radio access network (E-UTRAN): X2 general aspects and principles," Dec. 2008.
- [7] 3GPP TS 36.214 V8.7.0, "Evolved universal terrestrial radio access (E-UTRA): Physical layer — measurements," Sep. 2009.
- [8] A. Müller and P. Frank, "Cooperative interference prediction for enhanced link adaptation in the 3GPP LTE uplink," in *Proc. IEEE Veh. Technol. Conf.*, May 2010.
- [9] F. Calabrese, C. Rosa, M. Anas, P. Michaelsen, K. Pedersen, and P. Mogensen, "Adaptive transmission bandwidth based packet scheduling for LTE uplink," in *Proc. IEEE Veh. Technol. Conf.*, Sep. 2008.
- [10] 3GPP TR 25.814 V7.1.0, "Physical layer aspects for evolved universal terrestrial radio access (UTRA)," Sep. 2006.
- [11] 3GPP TS 36.211 V8.9.0, "Evolved universal terrestrial radio access (E-UTRA): Physical channels and modulation," Dec. 2009.