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Discrete-Event Simulation of Coordinated Multi-Point Joint Transmission in LTE-Advanced with Constrained Backhaul

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Abstract— Inter-cell interference in LTE-Advanced can be mitigated using coordinated multi-point (CoMP) techniques with joint transmission of user data. However, this requires tight coordination of the eNodeBs, using the X2 interface. In this paper we use discrete-event simulation to evaluate the latency requirements for the X2 interface and investigate the consequences of a constrained backhaul. Our simulation results show a gain of the system throughput of up to 120% compared to the case without CoMP for low-latency backhaul. With X2 latencies above 5 ms CoMP is no longer a benefit to the network.

Keywords—LTE-A; CoMP JT; Limited Backhaul; Discrete-Event Simulation

I. INTRODUCTION

With the current deployment of a next-generation global cellular technology such as long term evolution (LTE), the 3rd generation partnership project (3GPP) aims at providing a new and scalable system to address the demand for more performing mobile networks [1]. The use of orthogonal frequency multiple access (OFDMA) in the downlink direction allows for flexible spectrum sharing and dynamic allocation of users in both frequency and time. Since neighboring cells use the same set of frequency, user equipment (UE) located at the cell edge typically experiences high level of inter-cell interference (ICI) due to similar power levels from the serving eNodeB and the neighbors. Early approaches for ICI mitigation or cancellation to ensure ubiquitous network performances are present since release 8 [1]. The research and standardization moved beyond the release 8 currently available in most implementations to design LTE-Advanced (LTE-A), a 4th generation technology that introduces a series of advanced techniques to ensure even higher performances in terms of user throughput and coverage [1]. In order to cope with the ICI, advanced schemes for base stations cooperation are under evaluation. The most promising one – for the performances that can be theoretically achieved for cell-edge UEs – is considered to be coordinated multipoint (CoMP) joint transmission (JT) [2]. This technique requires the coordinated transmission of user data from multiple eNodeBs that belong to a cooperative cluster. In order for this technique to be effective, the multi-UEs scheduling done at the MAC sub-layer at each eNodeB must be coordinated within the cooperating cluster. Furthermore, when a UE is attached to an eNodeB, its data

from the internet is transmitted through the evolved packet core (EPC) at the S1 interface of that particular eNodeB and therefore is not available at the other cooperating eNodeBs. The eNodeB that is serving the UE is supposed to forward the data to the other transmission points (TPs). Together with the data, the serving eNodeB must provide the identity of the UE to serve as well as the channel quality indicator (CQI) value reported by the UE at the serving eNodeB in order for the cooperating eNodeBs to adopt the most suitable modulation and coding scheme (MCS) for the UE. This transmission is done by means of the X2 interface that exists between each pair of eNodeBs. The X2 interface is not necessarily a direct physical point-to-point (P2P) connection. In most implemented cases it is distributed over several links and L2 switches. This network between eNodeBs is typically referred to as backhaul and its characteristics – the latency in particular – are of primary importance for the feasibility of CoMP JT in real scenarios.

In this paper we present the results obtained using discrete-event simulation (DES) of an LTE-A network with CoMP JT. The rest of the paper is organized as follows: in Section II we present the most relevant works that are used to validate our results, Section III presents the key aspects of the model, while Section IV is focused on the results of the simulation campaigns. Finally, Section V concludes the paper.

II. RELATED WORKS

There is a relatively vast literature of studies on various CoMP schemes, in particular [2]. 3GPP presented it as a study item providing overall evaluation parameters and standardized scenarios covering both homogeneous and heterogeneous networks [3]. The work of [4] presents the results for an architecture very close to the one analyzed in this paper for the use of centralized scheduling and joint transmission. Reference [5] provides a comprehensive analysis of the main CoMP techniques, comparing the relative gains in both homogeneous and heterogeneous deployments. In [6] the authors present practical design choices in real scenarios, as is done by [2]. As regards the role of the backhaul for CoMP, in [7] the focus is on the topology and the clustering perspectives. Finally, 3GPP itself opened a new study on the impact of the backhaul in CoMP to coordinate the ongoing research [8]. The

characteristics of the backhaul listed in [8] are used in our work for the evaluation of the model.

III. SYTEM MODEL

A. System Architecture

The model has been developed with the DES tool OPNET modeler and it resembles scenario 2 in [3] with a more distributed approach where all the TPs are macro eNodeBs. Each eNodeB covers one cell and has an omnidirectional antenna with transmitting power of 46 dBm. We model an LTE frequency division duplex (FDD) system with 20 MHz bandwidth available in the downlink in LTE band 7 [1]. This leads to 100 physical resource blocks (PRBs) available at the MAC scheduler every scheduling turn (1 ms). The eNodeBs are connected via P2P links that have a unique attribute for the latency to model different realistic scenarios. The inter-site distance (ISD) is 500 m and the clustering is static with 3 eNodeBs. The system architecture is presented in Fig.1 where the center of the cluster is where the ICI is higher. The EPC is simplified and the S1 interface points directly towards an external traffic generator. The traffic generator models a full-buffer traffic model. There are two kinds of nodes in the network, eNodeBs and UEs. Even though most of the simulated scenarios have static UEs, the UE can be mobile, but its trajectory does not take it outside the initial cell since handover is not implemented. Both node models have an internal structure that resembles the layers of the LTE protocol stack [1] with physical and MAC for the UE, physical, MAC and radio link control (RLC) for the eNodeB. The eNodeB moreover keeps the physical and the MAC separated depending on the network interface they refer to – X2, S1 or radio. This modular structure allows extendibility and customizability of the model in terms of additional features without affecting the overall design. Each module is designed as a finite state machine (FSM) to ease the implementation of protocols. The modelling of the radio channel is done with a series of functions, each modelling a different characteristic and recording its result to the packet being transmitted (Fig. 2). These functions evaluate also the interfering transmissions of neighbor eNodeBs.
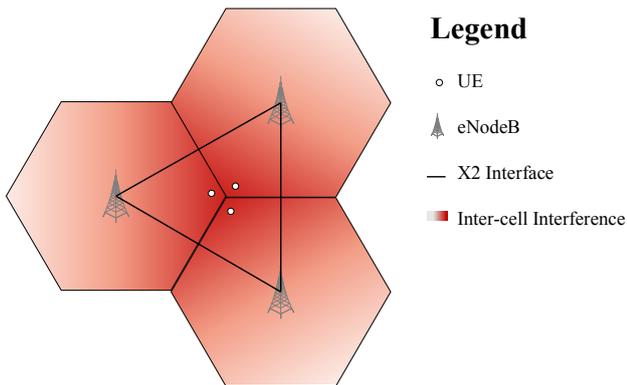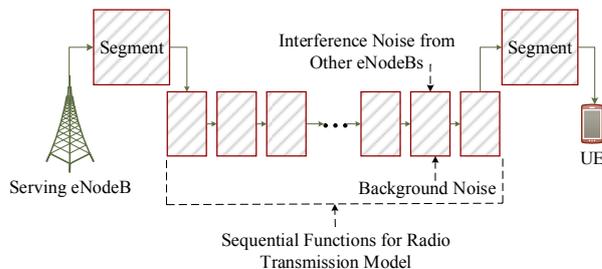

Fig. 1. System Architecture Model

Fig. 2. Radio Transmission Model

B. eNodeB Model

Packets from the traffic generator are received at the physical layer of the S1 interface and forwarded to the RLC that segments them according to the instructions provided by the MAC. These instructions consist on the value of bits per OFDM symbol that can be used for the PRBs assigned to that particular UE. This value is based on the latest available CQI value reported by the UE at the serving eNodeB. The number of OFDM symbols per PRB is fixed to 168 in our model, since 8 symbols are used for the reference signals (RS). The RLC sub-layer passes the segments to the MAC sub-layer for enqueueing and scheduling. In case CoMP JT is enabled, then the segment is also copied to the X2 interface. The modules for the MAC and the physical layers at the X2 interface forward a copy of the segment to each collaborating eNodeB including CQI and ID of the UE. Self-organizing network (SON) techniques are implemented in the modules of the X2 interface in order to discover the topology of the cluster and the identity of the neighbor collaborating eNodeBs. On the radio interface of the eNodeB, the scheduler is implemented at the MAC sub-layer. The scheduling algorithm is a modified round robin that also weights the size of the transmission sub-queue and the CQI value for each UE. In case CoMP is enabled, the scheduling decisions are coordinated within the cluster. This implies that a UE is scheduled in the same PRB by all the cooperating TPs in the cluster, which is necessary to successfully exploit the interference cancellation as signal quality enhancement. All the scheduled segments are passed to the physical layer where they are further segmented to accommodate the pattern of the 12 sub-carriers of a PRB. Moreover RSs are inserted to model the structure of a PRB [1]. The RSs use QPSK for robustness, therefore each OFDM symbol can carry 2 bits and a complete RS consists of 16 bits that are segmented into 8 parts that the UE then reassembles. The list of receiving channels that each transmitting channel shall evaluate is set statically during the initialization of the simulation. This list consists of the matching channels in terms of frequency of all the UEs in the network. This models the broadcast nature of radio transmissions: whenever a segment is transmitted on a channel, the segment is copied to all the receiving candidates listed in the transmitting channels.

C. Radio Transmission Model

The functions that model the radio transmission (Fig. 2) use the parameters of the nodes in the network to evaluate – among others – the delay that the segment should experience before reaching the UE, the matching between transmitter and

receiver channels – always successful as they refer to the static list built by the physical layer within the eNodeB – and so forth to compute a link budget. The most relevant functions are those that perform the evaluation of the nature of the incoming segments and the interference-management operations. The segments are evaluated according to the scheduling assignments of the eNodeB that are communicated to the UEs in the cell by means of the physical download control channel (PDCCH) [1]. The UE is therefore aware of the PRBs where it has been scheduled. Whenever a segment arrives from the serving eNodeB in one of the receiving channels of the UE, then the UE checks whether the channel belongs to one of its own PRBs. If there is a match, then the segment continues the sequence without any further modification. In case the channel does not belong to a PRB assigned to the UE, then it is marked as noise. When the segment received has not been transmitted from the serving eNodeB, then it is necessary to distinguish: in case CoMP JT is not enabled, then the segment is noise and its received power will contribute to increase the overall noise of the other transmissions. In case CoMP JT is enabled, then the scheduling assignments of the transmitting eNodeB are checked. In case the UE is scheduled in that particular PRB from the cooperating eNodeB, then the segment is labelled as a positive contribute to the SINR of the segment transmitted from the serving eNodeB since it is a copy of it. In case the UE is not scheduled in the particular PRB to which the receiving channel belongs to, than the segment is regarded as noise. These differences in the way that incoming segments are "labelled" are used to model the ICI. Whenever a segment is received on a channel where another segment is currently being received, their received power is used to compute the SINR. We modelled also the capabilities of the UE to convert successfully the interfering power of a cooperating segment. In fact, different UE types could be capable of converting only a fraction of the overall power of the cooperating segment. This is modelled by means of a parameter that acts as a weight to balance the fraction of power that is successfully converted and the one that is not – therefore contributing to the interference noise. An evaluation of the SINR in watt in such a scenario is presented in (1) where the P_{vs} is the received power of the valid segment, P_{cs} the received power of the cooperating segment, α in [0,1] is the parameter to model the capabilities, N_b is the background noise at 290 K and N_i the interference noise already experienced by the valid segment.

$$SINR_W = \frac{P_{vs} + \alpha * P_{cs}}{N_b + N_i + (1 - \alpha) * P_{cs}} \qquad (1)$$

Hence, $\alpha = 1$ models an ideal receiver (as is the case in our simulations) and $\alpha = 0$ models the case with CoMP disabled. The bit error rate (BER) is obtained by inserting the result of (1) in dB in (2) – g_p is the processing gain of the modulation – and mapping this result against the modulation table. This sets the number of error bits in the segment due to incorrect reception.

$$SINR_{dB}^{eff} = SINR_{dB} + g_p \qquad (2)$$

Synchronization information and cell identity are modelled with a dedicated signal sent periodically by the eNodeB to all the UEs on the central frequency (sub-carrier with index 599) and accepted by the UE only if it has been transmitted by its serving eNodeB.

D. UE Model

The UE retrieves the segments after the radio transmission. This node records the number of bits successfully received in case of data segments and the SINR in case of part of a reference signal. An average of the SINR values is used against the three modulation tables of LTE in order to determine the average BER experienced by the segments. This determines the current CQI index in order to have a blocking error rate (BLER) of at most 10%. According to the CQI reporting period set by the eNodeB, multiple values of the CQI are averaged and the result is fed back to the serving eNodeB. The node is also responsible to refresh the list of PRBs where the UE is scheduled.

IV.   SIMULATION RESULTS

In all the simulated scenarios we used the throughput measured at the physical layer of the UE as performance metric. Simulation parameters that are common to all the scenarios are those related with the network architecture presented in the model description as well as those presented in Table I. The CoMP gain in percentage is calculated as per (3) where T_c is the throughput with CoMP JT and T_{nc} the one without.

$$g_{CoMP}^{\%} = \frac{T_c - T_{nc}}{T_{nc}} * 100 \qquad (3)$$

TABLE I.   COMMON SIMULATION PARAMETERS

CQI Reporting Period	10 ms
Synchronization Signal Period	20 ms
ISD	500 m
Traffic Model	Full Buffer
Performance Metrics	Cell-edge UE and system throughput

The results of the CoMP gain in our simulations for cell-edge UEs in the cases with low-latency are comparable to those presented by [5], while the impact of the X2 latency in terms of system gain are comparable to the results presented in [4].

A. Impact of Cell Load and UE Distributions

The first set of simulations uses a perfect backhaul (0 ms of latency) to analyze the relation between the overall system performances, the cell load and the location of the UEs within it. For each value of the cell load, in case A (blue) all the UEs are located in the center of the cluster, while in case B (red) only 1 UE per cell is at the center of the cluster, while the others are around their own serving eNodeB (except for the case with only 1 UE per cell). The simulated time is 5 s. In Fig. 3 we present the results of the gain of the system throughput as summation of the throughput experienced by all UEs. On a system level in the case A it is possible to have a substantial gain of ~50% for up to 5 UEs per cell and of ~80% in the scenario with 10 UEs per cell. In Fig. 4 we present a comparison of the system throughput in the different cases.
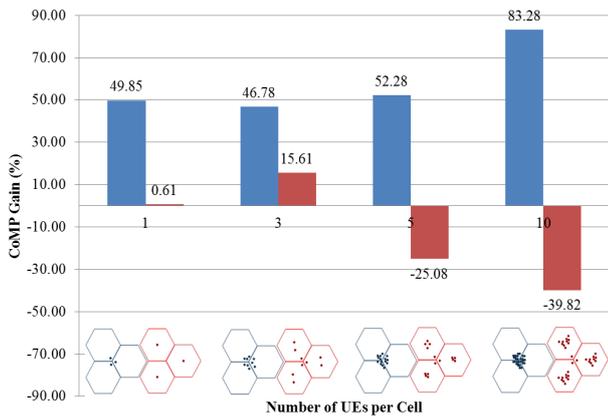
Fig. 3.   System Throughput Gain vs System Load and UE Distribution
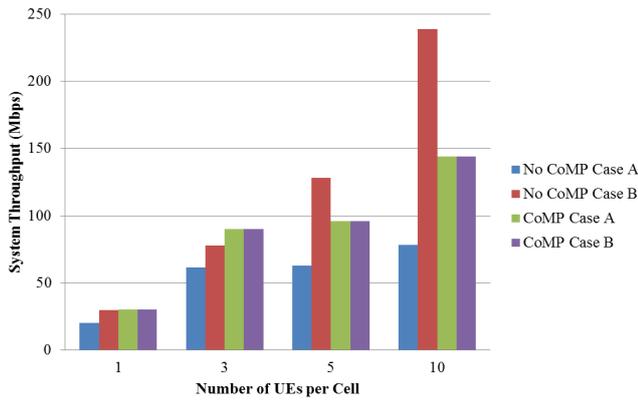

Fig. 4.   System Throughput vs System Load and UE Location

As can be seen, thanks to the differences between the cases A and B, the use of CoMP on a system level should be selectively targeted only to cell-edge UEs. Its use on the entire cell − and especially in cases with low interference − results even in a loss (cases with 5 and 10 UEs/cell). The feedback from the UE can be used as a trigger to enable CoMP, when the CQI goes below a certain threshold.

B. Impact of X2 Latency

The second set of simulations adopts the same performance metrics as above, but the scenarios have only 1 UE per cell. The UE in one cell moves at 3 km/h from the center of its cell towards the center of the cluster. The simulation duration is set to 3 minutes, approximately the time needed for the UE to complete its path and the X2 latency varies from 0 to 20 ms. This simulation set shows how the characteristics of the backhaul can delay the communication of the CQI updates over X2 as well as the data and the scheduling synchronization. Fig. 5 presents the variation of throughput for the pedestrian UE and it is possible to notice that with the latency above 5 ms, there is a loss compared to the case with no CoMP. This is evident if we take into account the gain as in the previous simulation set (Fig. 6). Shifting the perspective to the gain of the entire system (Fig. 7), the difference is even clearer.
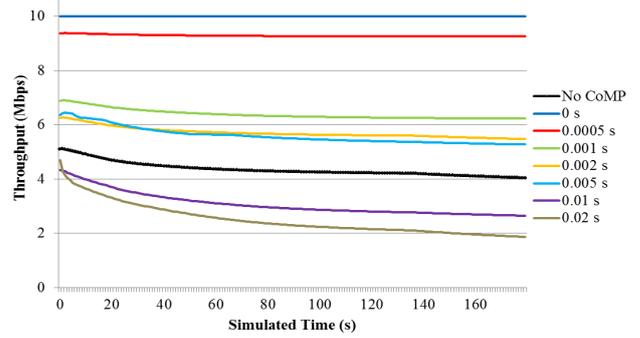

Fig. 5.   Throughput of Pedestrian UE varying the X2 Latency
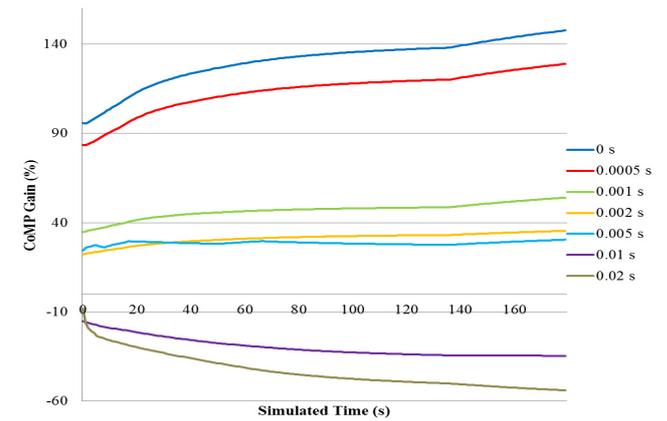

Fig. 6.   Throughput Gain of Pedestrian UE varying the X2 Latency
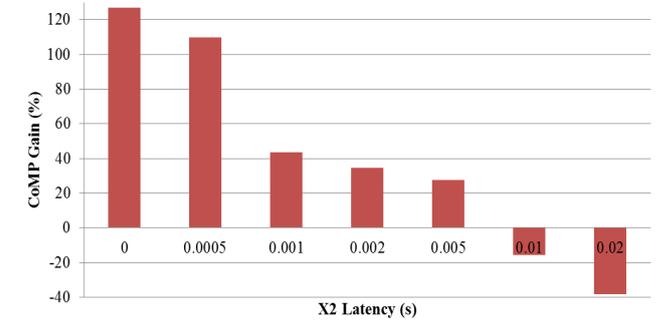

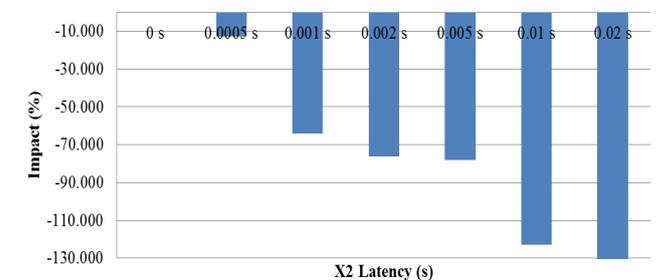Fig. 7.   System Throughput Gain vs X2 Latency

Fig. 8.   Impact of X2 Latency on Ideal CoMP JT Gain

The two static UEs in the other 2 cells of the system are negatively affected by delayed and out-of-sync information exchanged over X2. The overall impact of the latency of the backhaul network is summed up in Fig. 8, where we plot the loss due to the latency as compared to the maximum achievable gain in the ideal case with no latency. Therefore, values of the backhaul network latency below 1 ms ensure a gain above 120% that is progressively reduced till ~25% in case the latency reaches 5 ms. Our results show that higher values of the latency (10 and 20 ms) impact drastically the performances of CoMP JT leading to a loss of the system throughput compared to the case without cooperation of the TPs.

A final consideration that is common for both the simulation sets regards the role of hybrid automatic retransmission request (HARQ). HARQ takes care of the retransmission of the packets at a lower layer compared to transport-layer protocols [1] and it improves the number of bits received correctly for UEs receiving packets with high BER. In our model HARQ is not implemented. The retransmissions can improve the worst cases that we presented, especially those without CoMP with cell-edge UEs. Such an improvement in the cases without CoMP would reduce the gain due to CoMP, since the radio conditions when the cooperation is enabled are already good and they would not benefit from HARQ. On the other hand, HARQ could be a benefit also for scenarios with CoMP when we have UEs in areas with low ICI (as in the cases B in the first simulation set) since in this case the overall system performances resulted worse than without CoMP from our results. This would again slightly affect the ratio we used as measure of the CoMP gain.

V. CONCLUSIONS

In this paper we presented a novel approach for the study of CoMP JT and its requirements on a backhaul network with realistic constraints. The simulation results obtained using OPNET modeler show considerable gains of the system throughput related with specific scenarios. We concluded that the use of cooperation techniques in scenarios with static cell-edge UEs leads to improved performances in terms of system throughput in the range 50% to 80%. In scenarios with a pedestrian UE, ideal gains of up to 120% are achievable with latency below 1 ms. Considerable gains in the range 40% to 25% are achievable in the same scenarios as long as the latency is kept below 5 ms. For higher values CoMP JT should not be used at all since they imply a loss in the range of -20% to -40%. Our results show that 10 ms of latency on the X2 interface imply a loss of -120% in the gain that is achievable with a perfect backhaul and -130% in case the latency reaches 20 ms. Nevertheless, the use of CoMP JT techniques on UEs in areas with low ICI leads to worse performances than the scenarios with no cooperation at all. In these scenarios, our results show a loss of the system throughput due to the use of CoMP JT of around -25% with 5 UEs/cell and -40% with 10 UEs/cell. We therefore presented how the eNodeB shall trigger the cooperation within the cluster for a specific UE when the UE reports CQI values that indicate it is in an area with high ICI (cell-edge). It is possible to extend our results on a larger scale, by taking several of the basic clusters that we simulated to cover an urban area. This leads to a set of static clusters that are all interconnected between each other, even by means of

intermediate nodes or core network elements. In case the UE is at the center of a static cluster, then CoMP JT can be used as presented in this paper, provided that the X2 interfaces within the static cluster allow for considerable gains. In case the UE is not at the center of a static cluster, but still experiences high ICI, then the cooperation shall be established with those eNodeBs in the network that are connected via a X2 interface with latency below 5 ms, ideally below 1 ms. This leads to a multi-layer dynamic clustering that is UE-specific and adapts to the characteristics of the backhaul network between the TPs.

Our future works envisage the extension to advanced multiple antenna schemes, the impact of CoMP in handover scenarios, how CoMP affects the behavior of different kinds of traffic and applications and finally the modelling of a more centralized strategy for CoMP (Cloud-RAN) and its comparison with the distributed approach presented in this paper, taking into account the requirements of the backhaul network.

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