Modeling Coordinated Multipoint with a Dynamic Coordination Station in LTE-A Mobile Networks

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***Abstract*—Users located on the cell edge suffer from low data rates due to interference and poor reception. The Coordinated Multipoint technology targets this problem but it imposes overhead on the network, which can result in degradation of the Quality of Service. The Direct CSI feedback to Elected Coordination station architecture minimizes such overhead, resulting in improved data rates. Here, we analyze the performance of DCEC, Centralized, and Distributed control architectures for LTE-Advanced mobile networks in urban areas showing the advantages of the approach.**

Keywords— CoMP, CSI feedback, LTE-A, Signaling overhead

I. INTRODUCTION

With the rapid development of mobile devices and mobile internet, the number of mobile broadband users, the demand of data rates, and the total volume of data traffic are increasing very fast [1]. The number of mobile broadband subscriptions is growing globally by around 25% each year, and it is expected to reach 7.7 billion by 2021 [1]. The growth rate of mobile data traffic between the 1st quarter of 2015 and the 1st quarter of 2016 was about 60 percent. The network's data traffic is expected to reach 351 Exabyte by 2025 [2]. Consequently, service providers face two challenges: the massive number of users and the increasing demand of mobile data traffic by each user.

Coordinated Multipoint (CoMP) [3] was defined to improve data traffic for cell edge users [4]. In CoMP, the Base Stations (BSs) are grouped into cooperating clusters that exchange information and process signals and provide services to the users jointly. A CoMP cluster can be formed based on static or dynamic clustering algorithms [5]. Furthermore, CoMP enables User Equipments (UEs), such as mobile phones, to receive signals simultaneously from one or more transmission points in a coordinated or joint-processing method [4, 6].

CoMP enabled systems need accurate and up to date Channel-State Information (CSI) for adaptive transmission and appropriate radio resource management [4, 7]. To do so, the UEs estimate the CSI and report it to their serving BS periodically. This results in a significant increase of the feedback and signaling overheads [5, 6]. Furthermore, due to the large number of CSI feedbacks going around the network and the increasing queue sizes, the CSI feedback latency also increases. CoMP also incurs in infrastructural overhead [6, 8]: the networks need additional control units and low-latency links among the collaborating BSs, which might increase the network cost. This overhead mostly depends on the CoMP control architecture used and is different for the Centralized and Distributed control architectures [8, 9]. In the distributed architecture, there is signaling overhead, and it is more sensitive to error patterns. The centralized architecture uses a central unit for handling radio resource scheduling and it suffers from signaling overhead, infrastructure overhead and increases the CSI feedback latency [9].

With these issues in mind, in [10, 11] we proposed a CoMP control architecture named Direct CSI-feedback to Elected Coordination-station (DCEC), to reduce the signaling overhead and latency of the CSI feedback, which eventually will increase throughput [11]. As shown in [12], the throughput of a cell can increase by as much as 20% if the latency is reduced by 5 ms. In this architecture, one BS in the CoMP cluster acts as a Coordination Station (CS). Once a CS is elected, the UEs in a CoMP Cluster with the same cooperating set will send the CSI feedback to this CS only. Thereon, the CS will calculate the global CSI information, determining the cooperating set and will be in charge of scheduling. A Cooperating set is a set of BSs within the CoMP cluster that can jointly serve a UE [3]. This algorithm poses no increase in the error pattern, since all participating UEs send the CSI to the CS only after CoMP is established. Furthermore, no additional hardware is needed, so the costs for switching to such architecture would be minimal.

In order to compare the performance of the DCEC, Centralized, and Distributed architectures, we built models and ran simulations of various scenarios suggested by the 3rd Generation Partner Project (3GPP) [3, 4]. We used The CD++ toolkit [13] to model the different architectures. CD++ provides an environment to execute discrete-event models defined using the DEVS formalism [13]. In order to be able to compare the results, we model and simulate all the three control architectures.

The rest of the paper is organized as follows: In section 2, we discuss the background and related work. Then, in section 3, we describe the DCEC algorithm in detail. In section 4, DEVS model architectures are discussed in detail. Some simulation results will be seen in section 5. Finally we concluded in section 6.

II. BACKGROUND AND RELATED WORK

To improve the performance of mobile networks, 3GPP in LTE and 5G considers a number of technologies including massive Multiple Input Multiple Output, carrier aggregation, mm-wave communication, and CoMP [2, 14]. Among these,

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CoMP has been adapted as a key technology [4, 7, 14, 15]. CoMP improves the networks performance by mitigating inter-cell interference and scheduling resources. In CoMP networks, accurate and updated channel information plays a key role in achieving better performance. For this, the UE calculates the channel information and reports it to the BS through a CSI feedback message periodically so that the scheduler can perform Radio Resource Management and adaptive transmission for the UE.

There are two types of control architectures available for CoMP: centralized and distributed [8, 9, 16]. In the centralized architecture, a central unit (CU) is responsible for radio resource scheduling and processing the CSI feedback. The UEs estimate the channel state related to all the BSs in the cluster and send it back to their serving BS, which then forwards the local CSI to the CU. Finally, the CU calculates the global channel state and sends it back to the BSs in the cooperation set. This architecture suffers from signaling and infrastructural overheads as well as it increases the feedback latency. Instead, in the distributed case, the coordinated cells exchange channel state information over a fully meshed signaling network using X2 interfaces. The UEs estimate the CSI of all the cooperating BSs and send it to the corresponding serving BSs. After receiving the channel state information from the UE, the cooperating BSs exchange the CSI among themselves. Based on the acquired global CSI, the BSs schedule the resources independently. This architecture increases the signaling overhead, and is more sensitive to error patterns since they can be different for different BSs. This could potentially cause further performance degradation [8].

In [17], a distributed architecture for CoMP Joint Transmission (JT) is defined. It works over an IP backhaul network between BSs, and uses two time scales: (1) radio resources for CoMP JT are allocated every several 100s of ms; (2) modulation and coding schemes for link adaptation are calculated every ms. Gao et al. propose an algorithm for dynamic cell selection [18]. They extend the dynamic cell selection method to a Multi-Cell scenario, which originally is limited to one chosen transmission cell. In [19], CoMP architectures in different HetNet scenarios are studied, as well aas different CoMP schemes as well as the benefits and drawbacks of them.

For modeling and simulation of LTE and LTE-A networks, a variety of simulation platform such as NS3, OPNET Modeler, OMNET++ have been used [20]. Piro et al. [21] present a module developed for the simulation of the LTE technology using NS3. They focus on the aspects related to the channels and the physical and MAC layers of E-UTRA. Virdis et al. [22] use SimuLTE as a simulator for the data plane of the LTE/LTE-A Radio Access Network and Evolved Packet Core. This simulator is based on OMNeT++. We used CD++, which implements DEVS and Cell-DEVS theories [13]. DEVS provides a number of advantages for modeling and simulation [23]. A real world dynamic system modeled in DEVS is described as a composition of atomic (behavioral) models and coupled (structural) modelsIts hierarchical and modular nature allows the description of multiple levels, and enhances reusability. It reduces the computational time by reducing the number of calculation for a given accuracy. Furthermore, the same model could be extended with different DEVS-based simulators, allowing for portability and interoperability at a high level of abstraction. Finally, the use of formal modeling techniques enables automated model verification [23]. Performing a comparative analysis of different modeling and simulation techniques is outside the scope of this paper. Here, we want to study the performance of DCEC CoMP control architecture over the centralized and distributed architectures.

III. Coordination Station Election in CoMP

In case of DL transmission, the CoMP signaling overheads are related to the inherent need of CSI at the transmit end [6]. This global CSI feedback process could be different based on the architecture of CoMP. Two major challenges of the CoMP architectures are the CSI Feedback latency and the signaling overhead. Latency is inversely related to the throughput of the network, in particular for the coordinated schemes. However, if the feedback latency of the cooperating network is greater than the CSI feedback periodicity, the scheduler will receive a back-dated CSI. Our goal is to reduce the CSI feedback overhead and latency in order to improve the cell throughput.

The core mechanisms for overhead and latency reduction are network architecture optimization, faster feedback process, shorter transmission time interval (TTI) and QoS load differentiations [24]. Our architecture, named *Direct CSI-feedback to Elected Coordination-station* (DCEC), uses one of the BSs in the CoMP cooperation set as a *Coordination Station* (CS) dynamically [10, 11]. To elect a Coordination Station (CS) dynamically, we use the following algorithm:

1. *The UE estimates the CSI and send it to the serving BS.*
2. *The serving BS receives the CSI Feedback and calculates the CoMP cooperating set.*
3. *The serving BS declares itself as a CS, if a CoMP cooperating set contains more than one BSs,*
4. *The declared CS sends a CS-Declaration message to other BSs in the cooperation set.*
5. *After receiving the message, other BSs in the set compare their throughput with the received CS throughput.*
    a. *If received CS throughput ≥ to the recipient's throughput (or the current throughput) then*
       Current CS ID: = received CS ID.
       The recipient forwards the new CS information to the BSs in the cooperation set.
    b. *If received CS throughput = own throughput (or current throughput) and received CS ID < own ID (or current ID) then*
       Current CS ID: = received CS ID.
       The recipient forwards the new CS information to the BSs in the cooperation set.
    c. *If received CS throughput = current CS throughput and received CS ID = current CS ID: CS elected. Stop.*
    d. *Else, the recipient BS declares itself as the new CS and sends a CS-Declaration message to the other BSs in the CoMP cooperation set.*
6. *If cell throughput or cooperating set change, go back to 3.*

Figure 3 shows a simplified signaling procedure of DCEC.

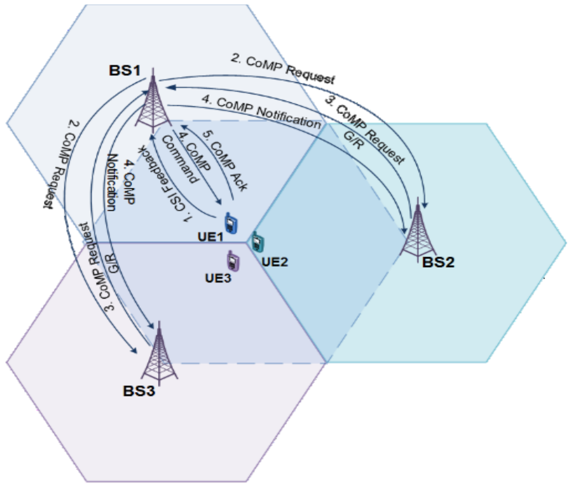


Fig. 1. Message transfer to elect CS and establish CoMP in DCEC-HetNet

First, the UE sends the CSI feedback to its serving BS. After receiving it, the BS calculates the *cooperation set* for the UE, checking the channel quality from the received CSI and comparing the predefined CoMP threshold (6dB [16]). If the *cooperation set* contains more than one BS, the serving BS initiates the election algorithm to elect the CS by sending a CoMP request message to the other BSs. After receiving the CoMP request, the recipients will check their own resources and compare the received throughput with their own. Based on availability of resources they will send back a request grant/reject message, including the highest throughput. After receiving the responses from the other BSs, the serving BS will make a decision about the CS and it will send the information to the other BSs. At this point, the serving BS will also send a CoMP command to the UE. Finally, the UE will reply using the ACK message and will switch to CoMP mode. After establishing CoMP, the UE sends the CSI feedback only to the CS. After the CS has been elected, all the UEs in the CoMP cluster with the same cooperating set will send the CSI feedback directly to the same CS only and the CS will perform scheduling. In this case, the CSI feedback message does not need to travel any additional X2, S1or fiber channels, which avoids extra latency of the CSI feedback transmission as well as reducing the overhead of the network.

IV. MODEL ARCHITECTURE

We designed a DEVS model to evaluate the performance of our proposal. The structure of the model is shown in figure 2.

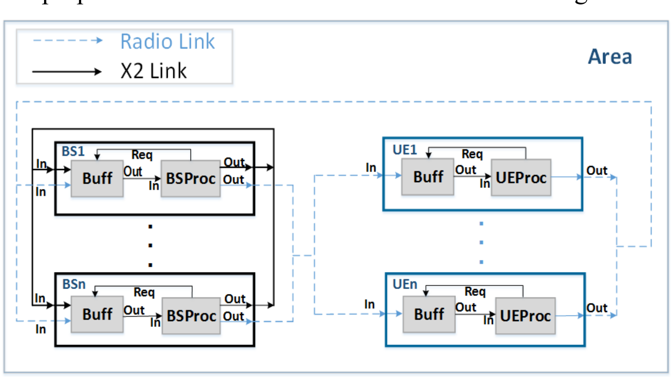


Fig. 2. Simplified DEVS model for CoMP control architecture

To study the control architecture of CoMP combined with DCEC we consider both homogeneous and heterogeneous networks as suggested in [3]. We use a homogeneous network with 19 cells. The Macro BSs within the cells are connected via X2 link. The top-level coupled model is the CoMP geographic area, which includes a number of cells. Each cell contains one BS and many UEs. We will not discuss the details of the clustering procedure and formation [5] as it is out of the scope of this paper. Each BS and UE coupled model is composed of two atomic models named *Buff* and *Proc*. The *UEProc* generates the CSI feedback based on the signal strength received from cooperating BSs and sends it to the BS *Buff* through the output port every 5 ms. The BS *Buff* acts as a buffer for the BS. Once the BS receives a message, the BS *Buff* pushes it in a queue. The message is popped out from the queue and forwarded to the *BSProc* when a request is received. *BSProc* executes the algorithm discussed earlier in this section to calculate a CoMP cooperating set and to elect a CS. The black solid links represent X2 links, and the light blue dashed lines represent air links. Moreover, the number of BSs and UEs can be changed based on the simulation scenario.

Figure 3 shows a simplified UML class diagram of the model discussed above. The BS class represents the BSProc, and the UE class represents the UEProc. BS is characterized by id, position, transmit power, frequency, throughput, etc. UE is characterized by id, position, transmit power, frequency, etc.

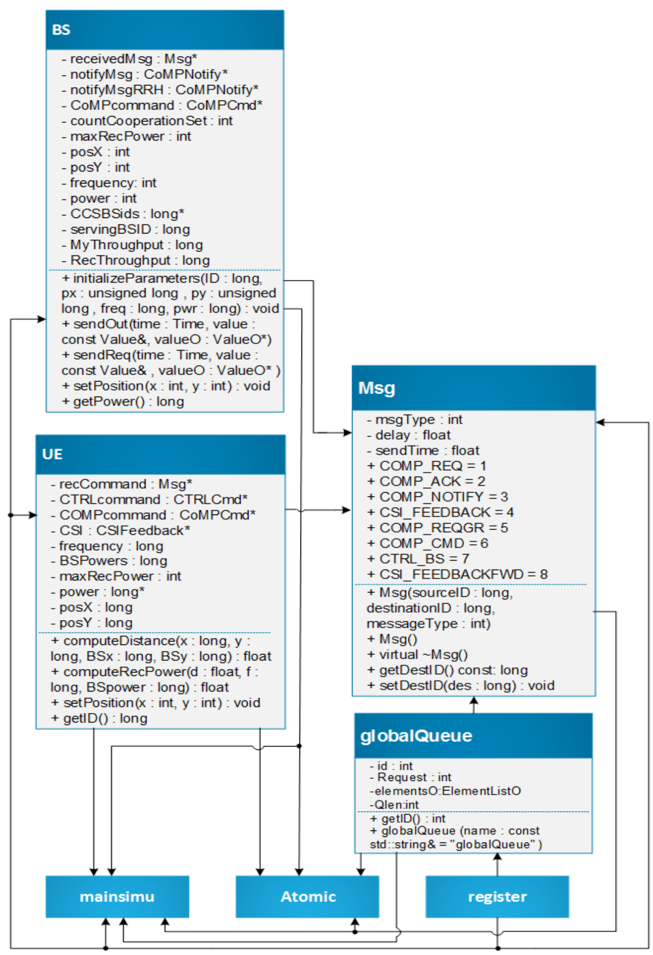


Fig. 3. Simplified class diagram of the model

In order to differentiate between different messages going around the network, eight types of messages were used. Below is a brief description of each message:

- CRTL_BS: BSs and RRHs send system information to UEs.
- CSI_FEEDBACK: contains the channel state information sent from the UE to the BS.
- CSI_FEEDBACKFWD: RRH uses this message to forward the CSI received from UE to BS it is connected.
- COMP_REQ: a request sent from the serving BS to other BSs in the CoMP cooperation set to join CoMP and elect the CCS.
- COMP_REQ_G_R: a grant/reject message sent from the recipient BSs to the serving BS based on the availability of resources.
- CoMP_COMMAND: a command sent from the serving BS to the UE informing about the elected CCS.
- COMP_NOTIFICATION: a notification sent from the serving BS to other BSs with in the cooperation set to notify about the establishment of CoMP and the elected CCS.

COMP_ACK: an acknowledgement of the receipt of the command sent from the UE to the serving BS.

To evaluate the potential of the DCEC control architecture, we ran a series of simulations on this model, based on the initial conditions summarized in table 1 [25, 26]. Based on [9, 25] the CSI feedback frequency has been set to 5 ms.

TABLE 1: SIMULATION ASSUMPTIONS

Parameters	Values
Number of macro BS	19
Number of UEs	50, 100 , and 200
UE Distribution	Uniform: randomly in CoMP area
UE arrival	Poisson: 6 AM-6 PM. Peak: 10 AM
Frequency	2000 MHz
BS Transmit Power	43 dBm
Cell Radius	500 m
Antenna gain	12 dBi (BS) and 0 dBi (UEs)
MCL	70 dB
LogF	10 dB
Cell Throughput	Uniform: 1 to 6
CSI Feedback periodicity	5 ms
CoMP Threshold	6 dBm
Traffic Model	Full buffer

As seen in the table, the transmit power for a BS is set to 43dBm [25, 27]. The received signal power at each UE is calculated based on the following formula [25]:

$$P_r = P_t - Max\left(L_{path} - G_t - G_r, MCL\right) \quad (1)$$

Where P_r is the received signal power, P_t is the transmitted signal power of the BS, L_{path} is the path loss, G_t is the transmitting antenna gain and G_r is the receiver antenna gain. The Minimum coupling loss (MCL) is considered to be 70 dB [25].

$$L_{path} = \mathrm{L} + \mathrm{LogF} \quad (2)$$

Where L is calculated based on the following formula [25]:

$$\mathrm{L} = 40 * (1 - 4 * 10^{-3} * B_h) * \log_{10}(d) - 18 * \log_{10}(B_h) + 21 * \log_{10}(f) + 80dB \quad (3)$$

Here, B_h is the base station height, which we consider to be 15 meters, d is the distance between UE and BS and f is the carrier frequency. In our simulations, the UEs calculate the received power based on the above formula, generate a CSI feedback message and send it to the BSs. Furthermore, the BSs generate the cell throughput at random to elect the CS. Based on the literature in this area, we considered the CoMP threshold as 6dB [16] to find the CoMP cooperating set dynamically.

V. SIMULATION RESULTS

In this section, we explain different simulation scenarios and the results we obtained for the proposed control architecture and two other conventional control architectures discussed in the previous sections. In order to evaluate and compare the results, different simulation scenarios with varying number of UEs were conducted for each architecture. To omit abnormalities, 10 simulation runs were conducted for each simulation scenario and the margin of error was calculated based on a 95% confidence interval. The results were obtained and analyzed for comparison of *delay* and number of *CSI feedback* messages. To mimic the real world, UEs were set to start transmitting the CSI feedback based on a Poisson distribution within a 12 hour period (from 6 AM to 6 PM) with the peak request rate being located at 10 AM [28]. Figure 6 demonstrates the distribution of the average request start time for 10 runs for 100 UEs.

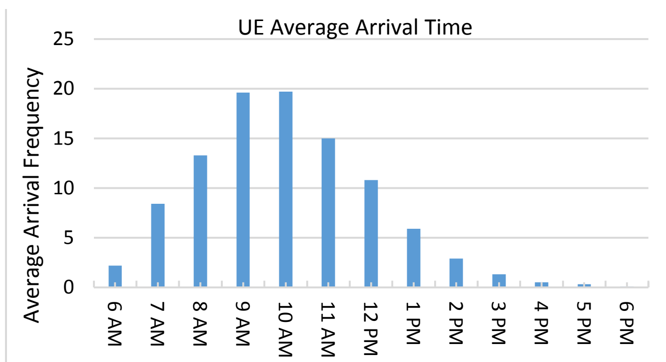


Fig. 6. Average distribution of request start time for a sample run for 200 UEs

One of the factors that directly effects the download and upload rates resulting in a change in user experience, is the number of feedback messages in the network. Reducing the number of messages in the results in a reduced delay. As shown in [12], the throughput of the cell can increase by as much as 20% if the latency is reduced by 5 ms. One of the aims of DCEC is to reduce the number of CSI feedback messages transmitted through the network. Figure 7 demonstrates that by the use of DCEC, the number of feedback messages can significantly be reduced in the network resulting in better data rates. The results are presented by considering a margin of error for 95% confidence interval. In order to make the graphs more readable, the margin of error is only shown for points that lay exactly on the full hour.

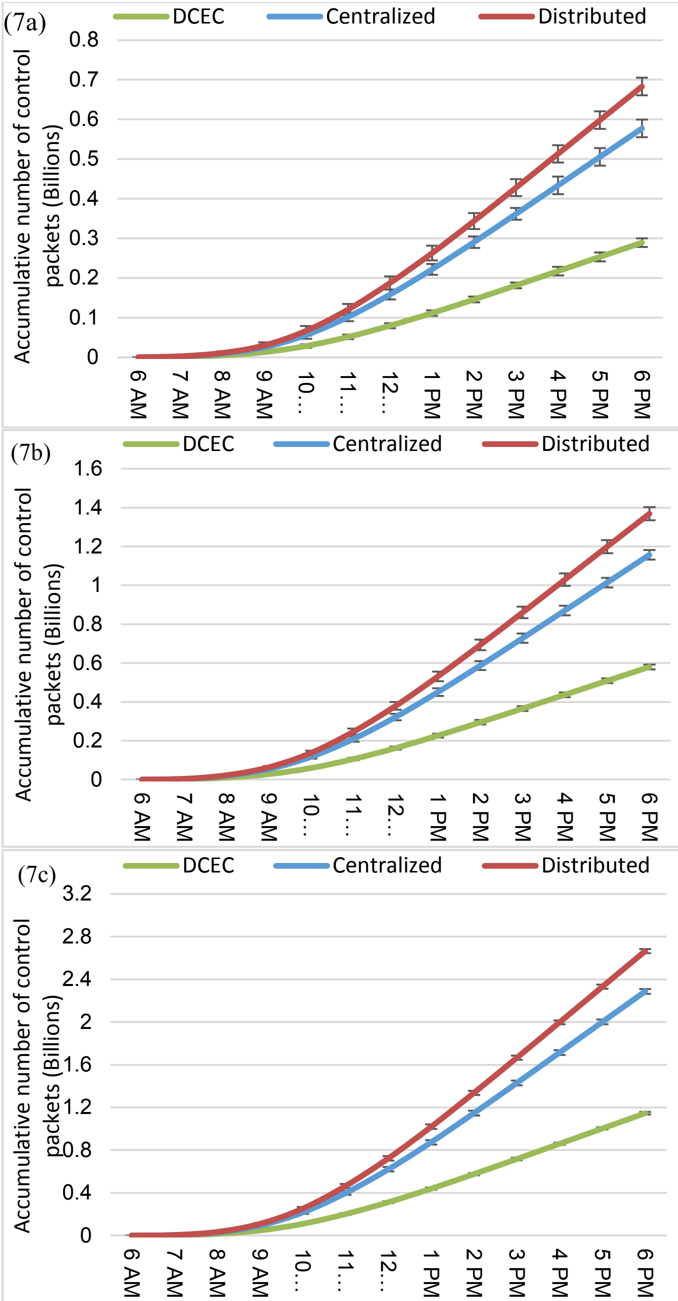


Fig. 7. Accumulative number of packets for (a) 50, (b) 100 UEs, (c) 200 UEs

As seen in Figure 7, DCEC reduces the CSI feedback messages in the network by as much as 50%. This is because after a base station is elected to act as the CS, no messages travel over the backhaul. This increases the upload and download rates, and eliminates the possibility of outdated CSI messages.

We also calculated the number of CSI feedback messages sent in 0.3 min timeframes. This allows us to investigate further the overhead imposed on the network by running DCEC. Figure 8 shows the number of packets sent through the network. As seen in figure 8, DCEC performs worst in the initial stage as it is executing the election algorithm whereas the other two algorithms do not need such action. As time goes by, the DCEC approach outperforms the other two approaches. Furthermore, by comparing the figures for 50, 100, and 200 UEs, it can be seen that DCEC is less sensitive to the addition of extra UEs.

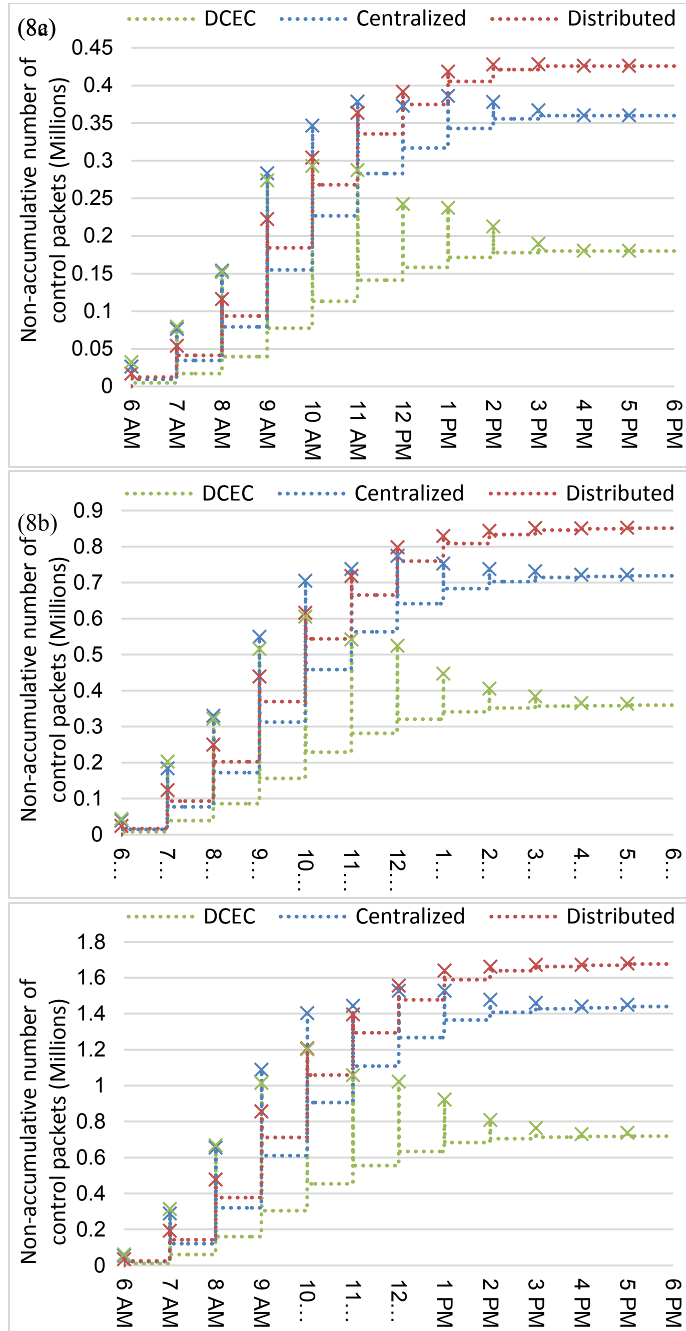
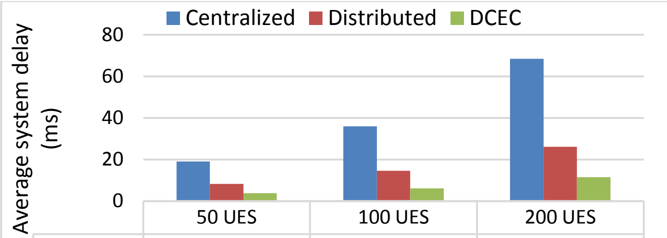


Fig. 8. Non-Accumulative number of packets for (a) 50, (b) 100, (c) 200 UEs

The increase in CSI feedback messages results in higher delay. The delay was measured for every CSI feedback sent by the UE. To find the average system delay, the average of all the measurements were calculated for 10 separate simulation runs. Figure 9 shows the average delay of the entire system for different number of UEs.



	50 UES	100 UES	200 UES
Centralized	19.12916667	36.05893958	68.4513175
Distributed	8.3464765	14.65879069	26.27468519
DCEC	3.831310042	6.127926806	11.63949131

Fig. 9. Average system delay for 50, 100, and 200 UEs

The above figure shows that DCEC imposes the least amount of delay on the network while the centralized approach imposes the most delay. It can be confirmed once again that the DCEC approach is less sensitive to the increase in the number of UEs in the network. This allows for DCEC to be a good fit for both crowded and uncrowded areas. Given that DCEC does not need any additional hardware for implementation, switching to DCEC could decrease the number of CSI feedback messages, and increase the upload and download rates at minimal cost.

VI. Conclusion

We presented new results highlighting the potential of the DCEC control architecture. The simulation results show that DCEC reduces the number of CSI feedback messages, resulting in lower delay and higher data rates. This study can be further expanded and applied to HetNets. Also, results can be obtained for more number of users and users that do not stay in the CoMP area for the entire length of the simulation.

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