DEVS-based Modeling of Coordinated Multipoint Techniques for LTE-Advanced

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Abstract

Considering the ever-increasing bandwidth demand of the users in cellular networks, there have been ongoing investigations of new standards to support users' requirements and increasing their performance in mobile networks. One of the more promising mobile communication standards for the Fourth Generation (4G) cellular systems is the Long Term Evolution Advanced (LTE-Advanced) standard. This technology provides an order of magnitude higher data rates and improves the users' quality of service by using a number of technologies including Coordinated Multipoint (CoMP) processing. In this paper, we have used the Discrete Event System Specification (DEVS) formalism to model a mobile network using two approaches of CoMP: namely, coordinated scheduling/beamforming and joint processing. The DEVS approach confirms that these approaches decrease the interference level resulting in cell edge users experiencing higher level of performance.

1. INTRODUCTION

Future mobile networks will need to support large numbers of user equipment (UE) with high data rate demands. In order to achieve these goals, telecommunication service providers are improving related standards to support the required quality of service for their users. One of the promising mobile communication standards for the Fourth Generation (4G) cellular systems is Long Term Evolution Advanced (LTE-Advanced). It has been standardized by the 3rd Generation Partnership Project (3GPP) as a backward-compatible enhancement of the Long Term Evolution (LTE) standard [1]. This standard meets or exceeds the International Mobile Telecommunication (IMT)-Advanced requirements and is considered as a candidate for IMT-Advanced systems [2, 3].

To overcome the transmission barriers such as Inter-Cell Interference (ICI) and to support the high data rates as well as meet the IMT-Advanced requirements a number of technologies including advanced Multiple Input Multiple Output (MIMO), Orthogonal Frequency Division Multiplexing (OFDM), wireless relays, enhanced Inter-Cell Interference Coordination (eICIC) and Coordinated Multipoint (CoMP) are employed in LTE-Advanced [4].

ICI is a major bottleneck for the cellular networks performance [5]. In particular, this problem affects cell edge users' performance. It also acts as a barrier for mobile network standards coming close to their theoretical rates [6]. In fact, ICI is a result of using the same radio resources in different cell in an uncoordinated way [7]. To overcome these problems different types of techniques such as interference cancellation, interference coordination and interference randomization have been investigated [3, 8, 9, 10].

As it was mentioned, CoMP is a key technique in LTE-Advanced to mitigate co-channel interference and increase per user capacity. CoMP refers to a set of base stations (BSs) that are coordinated jointly and dynamically. With the implementation of CoMP BSs can support joint scheduling of transmissions and provide joint processing of the received signals in order to improve system performance. Specifically, CoMP BSs form coordination sets for which the main objective is to manage interference to enhance the performance of UEs especially for the cell edge users [11]. It is clear that high data rates are relatively easy to maintain when one is close to the BS, but as distances between UE and BS increase, it is more difficult to maintain a high data rate. The most challenging situation occurs when UE is close to cell edge. In this case, besides the lower signal strength, because of the distance between UE and base station, the interference level from the neighboring BSs is higher as the UE will be closer to them. By using an approach of coordinating and combining signals from multiple antennas and BSs, it is possible for mobile users to have high quality and consistent performance when they require high-bandwidth services for different applications. This is supported regardless of their distance from the cell center. In fact, CoMP increases data transmission rates and ensures consistent service quality and throughput on LTE wireless broadband networks. Both users and network operators benefit from CoMP advantages. To support this feature in LTE-Advanced networks, BSs and UEs require the exchange of scheduling decisions, hybrid ARQ feedback, channel state information (CSI) and other control information with each other [3]. BSs share the received messages from their UEs with other BSs in coordination set through the 3GPP standard interface denoted as X2 [3].

Considering the way that control information is made available at the different transmission points, CoMP can be implemented in two ways: centralized and distributed. In the centralized CoMP transmission approach, a central unit is the entity where all channel information and data from all UEs in the supported area by coordination set are available. This central entity can be an assigned base station or a higher order entity in the LTE network. For downlink transmissions UEs estimate the channel status and then they feedback this information to the serving cell. Once the serving cell receives this information from its UEs, it forwards this information to the central unit that is responsible for the scheduling operations. After computing the parameters related to scheduling, the central unit sends the results to the coordinated BSs in the coordination set. The main challenge in this architecture is the latency parameter to support effective exchange of information between BSs in the coordination set. In addition, because all BSs will need to send all of the UEs status information and data to the central unit there will be significant signaling overhead on the backhaul.

In distributed CoMP, the UEs send back the channel status to their serving BSs in the coordination set and this information will be forwarded from the serving BSs to the coordinating BS. Hence, each BS receives all of the UE feedback, including that related to other BSs in the coordination set, and each BS can perform its scheduling operation in a coordinated manner. It is worth mentioning that the schedulers are identical hence similar inputs result in similar outputs. The main advantages of this architecture are reduced infrastructure cost and signaling protocol complexity. These benefits are possible because there is no dedicated central unit in this architecture, which results no need for BSs to communicate with it, and hence, there is no need for communication links between a central entity and the CoMP BSs. It should be noted that in a distributed architecture a BS might be selected as a temporary CoMP coordination entity for a given CoMP session. A serious problem in this kind of architecture is handling the errors on the same feedback information on the different feedback links [1, 2, 7, 12].

There are two schemas for CoMP in LTE-Advanced with respect to the way the data and scheduling information is shared among BSs: Coordinated scheduling/Beamforming and Joint Processing (Figure 1). In the latter approach, the BSs in the coordination set share their data as well as the channel state and scheduling information with other BSs. In the former approach, the exchange of data is not required and the BSs just need to share the channel state information and the scheduling information. In other words in the Joint Processing scheme the data to be transmitted to a single UE, is transmitted from BSs simultaneously in coordination set. This increases the signal quality at the UE side and decreases the interference level. However, at same time the amount of data that needs to be exchanged over the backhaul is very large. In Coordinated Scheduling/Beamforming, each UE is served by one of the BSs in the coordination set (the serving BS) and the scheduling decisions are selected in a way to control interference among the BSs in the coordination set. Therefore, in this case the BSs just need to share scheduling information and the UE data does not need to be conveyed to all BSs in coordination set since there is only one serving BSs for one particular UE at any given scheduling instance [1, 3, 4, 7, 13].

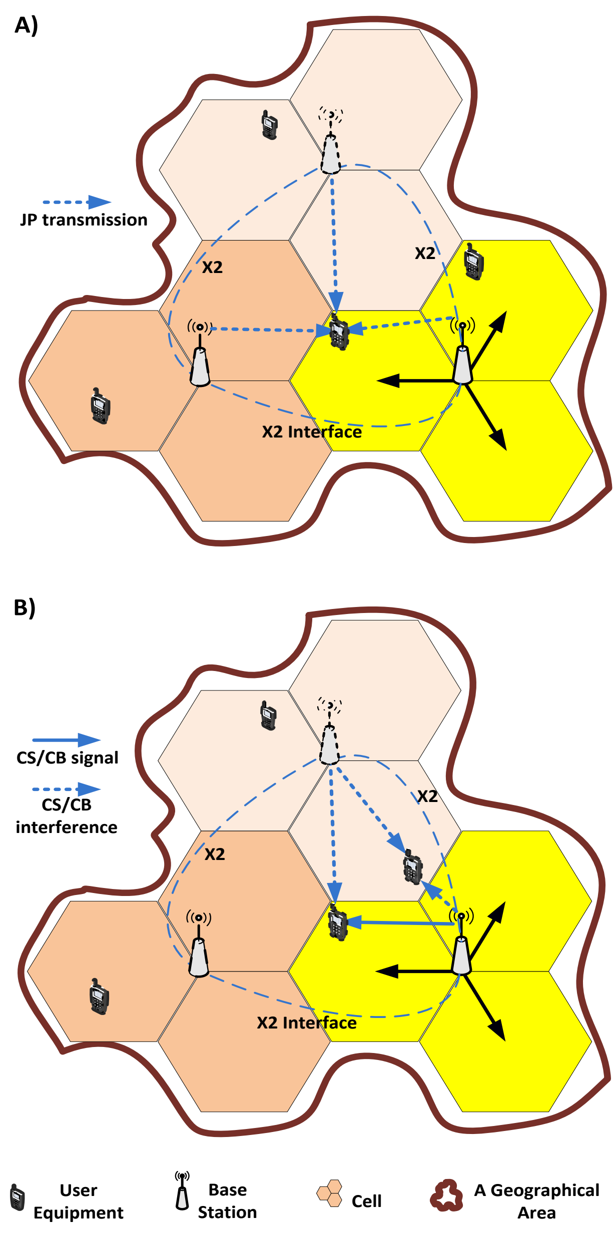

Figure 1. A) JP transmission B) Coordinated Scheduling/Beamforming in LTE-Advanced

2. BACKGROUND

Discrete Event Systems Specification (DEVS) is a formal framework for modeling and simulation. It is based on system theory concepts. DEVS theory provides a precise methodology for representing models, and it presents an abstract description of the system of interest. It supports a formal background for modeling both discrete and continuous systems. According to DEVS formalism, a real system can be defined as a composition of atomic and coupled components. This composition has a hierarchal nature. Atomic models are the basic blocks and a set of two or more interconnected atomic models can form the coupled models. In addition, a coupled model itself can be composed of atomic or coupled models [14].

A DEVS atomic model is formally specified by:

$M = < X, Y, S, \delta_{int}, \delta_{ext}, \lambda, t_a >$,

Where $X = \{(p, v) \mid p \in IPorts, v \in X_p\}$ is the set of inputs events, where $IPorts$ reveals the set of input ports and X_p shows the set of values for the input ports. $Y = \{(p, v) \mid p \in OPorts, v \in Y_p\}$ is the set of outputs events, where $OPorts$ reveals the set of output ports and Y_p shows the set of values for the Output ports. S is the set of sequential states. $\delta_{int}: S \rightarrow S$ is the internal state transition function. $\delta_{ext}: Q \times X \rightarrow S$ Is the set of external transition function where $Q = \{(s, e) \mid s \in S, 0 \leq e \leq tas$ and e is the elapsed time since last transition function. $\lambda = S \rightarrow Y$ is the output function and $ta: S \rightarrow R_0^+ \cup \infty$ is the time advance function [14].

The above definition means at any given time, a DEVS model is in a state $s \in S$ and it remains in that state for a lifetime defined by $ta(s)$, unless an external event occurs. When the state duration expires, $e = ta(s)$, the model will send the output $\lambda(s)$ through the desired output ports and then it performs an internal transition function to determine the new state by $\delta_{int}(s)$. On the other hand, a state transition can also happen due to the arrival of an external event. In this case, the external transition function determines the new state, given by $\delta_{ext}(s, e, x)$ where s is the current state, e is the elapsed time since last transition and $x \in X$ is the external event that has been received. The time advance function $ta(s)$ can take any real value from the defined interval in the definition. A state with $ta(s) = 0$ is called a transient state which will lead to an instantaneous internal transition. Also if $ta(s) = \infty$, the state is said to be passive such that the system will remain in this state until receiving an external event. It is worth mentioning that the last situation can be used as a termination condition.

3. Modeling of Mobile Network in DEVS

As it has been shown in Figure 1, mobile networks or cellular networks are radio networks distributed over land areas known as a cell. Each cell has at least one fixed transceiver called a Base Station (BS). These cells support radio coverage over a geographic area by overlapping their coverage areas and each cell includes at least one BS and a number of users (i.e. UE's). Figure 2 demonstrates a simplified DEVS model hierarchy for the mobile network we will discuss.

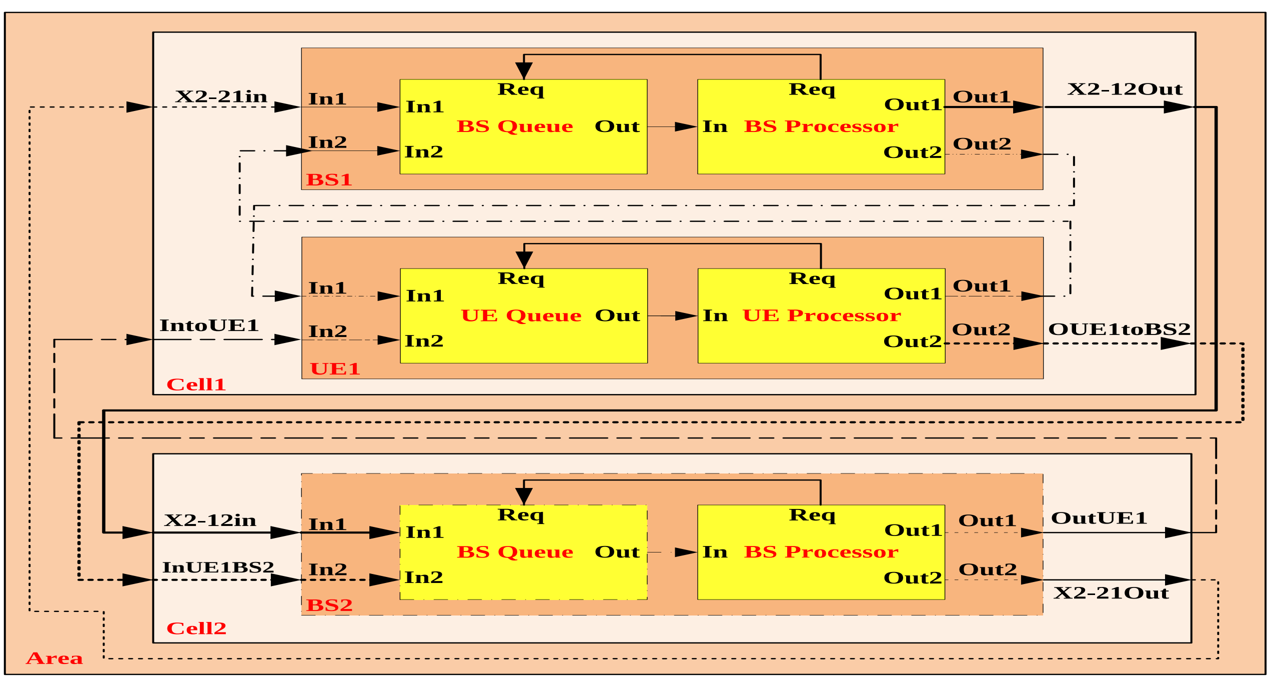

Figure 2. Simplified DEVS model hierarchy for mobile network model

The model in the top level includes an area with numerous cells. Each cell has one BS and it can have various UEs. Area, Cells, BSs and UEs are defined as DEVS coupled models. Each of the BSs and UEs consist of two atomic models including a Processor and Queue. The UE's processor functionality is different. UEs are able to send or receive data packets to/from each other and they send control information (such as CSI for BSs). The control packets include the base information for BSs. This information is employed by the BS to determine the UE's status. For example according to this information, a serving BS can determine if a certain UE will be scheduled to operate in normal mode or CoMP mode and if it scheduled to be in CoMP mode, which BSs are in the coordination set. In such a case, the serving BS has to send data and control information to the other BSs in the CoMP session. Likewise based on these control packets a BS can understand that a UE wants to move from one cell to another cell or even that a UE wants to leave the Area. In such a scenario, BSs should handover both data and control packets to other BSs. In case of data packets, BSs forward the packets according to their destination. Control packets, depending on the information they carry, will be distributed between the BSs in the same coordination set, or into the entire network. An example of the latter case is a UE moving from one cell to another. Although in the baseline approach of LTE networks, mobility updates are usually handled by a central entity denoted as the Mobility Management Entity (MME), in this model we consider X2 based handover. In this situation, the serving cell will notify its neighbor BSs and they themselves will notify their neighbors. Using this approach, the entire BSs in the mobile network will understand that a certain UE changed its serving cell, and they will update their routing tables. If they want to forward a packet for that UE, they will send it for the new address. In previous sections, we mention that the BSs communicate with each other through X2 interfaces, and based on the above description it is clear that the X2 interface characteristic can have a huge effect on the overall network performance.

In this mobile network model, the message structure consists of six digits. Four types of messages have been defined for this model. Messages types are (i) UE to UE, (ii) UE to BS, (iii) BS to UE and (iv) BS to BS. UE to UE messages support data and ACK exchanges between UEs. It is worth mentioning that UE to UE exchanges are being considered as part of 3GPP release 12 and are referred to as Device-to-Device (D2D) solutions. UE to BS messages are used when a UE wants to send information about its status to the serving BS. These types of messages can be employed to support UE operation mode or UE mobility. BS to BS messages are used by BSs to update each other about the network status.

In DEVS formal definition, the UE Queue (UEQ) has corresponding input ports for each of the BSs. In addition, another input port denoted as the request port, is used by the Processor to indicate to the Queue that it can accept new jobs. UEQ has just one output port to the Processor and the output function sends the first member of Queue for the Processor through that port. UEQ has three states: namely, Idle, Push and Pop. The external transition function receives messages from the input ports and initiates appropriate state transitions. Furthermore, the internal transition function defines state changes according to current state and the time advanced function controls the required timing configuration during the simulation.

DEVS formal definitions of the UE Processor (UEP) and BS Processor (BSP) describe these components behavior as well. In both cases the external transition function receives messages from the input ports and initiates appropriate state transitions. Furthermore, the internal transition function defines state changes according to current state. In UEP, the output function sends out a new generated packet or ACK for a received packet or control information for the serving BS. Note that if this UE is scheduled in CoMP mode, it will send control information for the coordination set. In BSP, the output function sends out forward link data packets or their ACK packets toward their destination. In addition, it will send control messages for neighboring BSs and its UEs if it is required. Figures 3 and 4 represent the DEVS graph of UE and BS Processors respectively.

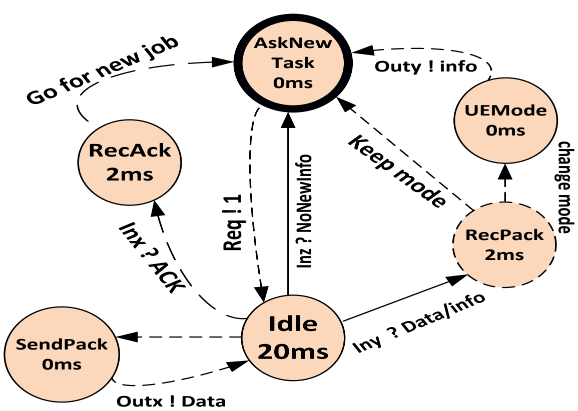

Figure 3. UE Processor DEVS graph

4. Implementation on CD++

The CD++ toolkit provides a framework for programming DEVS models. A model file is used for defining the DEVS coupled model hierarchical structure and coupling (Figure 5). A header file is used for defining atomic models as a class. Ports, variables and state definitions of an atomic model can be found in this file. Users can implement definitions of functions such as δ_{int}, δ_{ext} and λ in the CPP file, according to the C++ programming language convention.

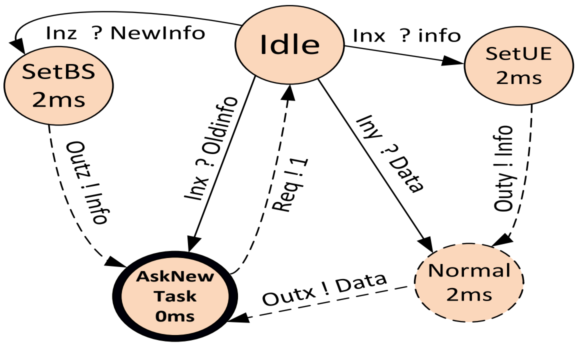

Figure 4. BS Processor DEVS graph

```
[top]
components : Cell1 Cell2 Cell3 Cell4 Cell5 Cell6 Cell7
Link : X2-12Out@Cell0  X2-12In@Cell1
...
[Cell1]
components : BS1  UE1 ...
in  :  X2-21In   In1toUE1 ...
out : X2-12Out  OUE1toBS2 ...
Link : X2-21In   In1@BS1
Link : Out1@UE1  In2@BS1
...
Link : IntoUE1   In2@UE1
...
[BS1]
components : BSprocessor1@BSprocessor
             BSQueue1@BSQueue
in  : In1  In2 ...
out : Out1  Out2 ...
Link : In1  In1@BSQueue1
Link : In2  In2@BSQueue1
...
Link : Out@BSQueue1  In@BSprocessor1
Link : Req@BSprocessor1  Req@BSQueue1
Link : Out1@BSprocessor1  Out1
Link : Out2@BSprocessor1  Out2
...
[UE1]
components : processor1@processor
             Queue1@Queue
in  : In1 In2 ...
out : Out1 Out2 ...
Link : In1 In1@UEQueue1
Link : In2 In2@UEQueue1
...
Link : Out@UEQueue1 In@UEprocessor1
Link : Req@UEprocessor1 Req@UEQueue1
Link : Out1@UEprocessor1 Out1
Link : Out2@UEprocessor1 Out2
...
```

Figure 5. Simplified Model file of an Area

In this implementation of a mobile network if we consider the model hierarchy as a tree then the root of the tree will be an area and the leaves of the tree will be atomic models. Our model implementation was started by defining atomics models. Their functionality has been tested separately by using appropriate Event files. In the next step, coupled models are defined according their structure that was described in the previous sections. Each of the coupled models has also been tested separately. Figure 5 shows that how in the final step a model file was produced in order to define all of the components and their interconnections. Figure 5 shows that in this mobile network model, the Area as a top model consists of number of cells. To support the connections among its components we have defined links between them. In the next step, each of Area's coupled components has been defined (i.e. such as Cell1). It can be seen that at this level each of the coupled models has inputs and outputs too. These ports should be connected to the related ports of their components. This process continues until we define the entire DEVS coupled model in the Model file.

5. Simulation Results

As was mentioned earlier each atomic and coupled component has been tested separately with different simulation scenarios, which were injected to the network through an event file. The final model, which is an area with a set of cells, BSs and UEs, has been tested under a variety of random simulation scenarios. In this case, UEs randomly generate packets as a source for a desired destination and they send these packets through the network.

When a UE is working in a normal mode, it communicates with other entities through its serving BS. In such a scenario, a serving BS of a first UE will route the received packets of this UE through the LTE network to the serving BS of the second UE. The serving BS of the second UE will then transmit the packet to the second UE. In addition, the BSs receive the ACK of these respective packets on the reverse link. Figure 6 illustrates a sample of such communication between UE0 and UE2. For this example, BS0 and BS4 are the serving BSs for UE0 and UE2 respectively. UE0 produced data packets and UE2 has created an ACK packet for each of received data packets from BS4.

If a UE is in cell edge zone its serving BS can decide that it is a candidate for working in CoMP mode. According to this scenario, the serving BS can create a coordination set for that UE to improve its performance. As it was mentioned in previous sections, there is a predefined messaging structure for these simulations. Receivers can make decisions according to the structure of the received messages. For example in joint processing simulations a UE can send a message for its serving BS to announce that it can sense other BSs signals and it can work on CoMP mode. This message includes the BSs identification numbers as is illustrated in Figure 7. In this figure, the second line shows the message with related information about CoMP mode that a UE sent for its serving BS.

```
Time          Port  Value   //UE0 Processor out
...
00:00:00:020  0  020001
...
00:00:00:052  0  020002
...
                            //BS0 Processor out
...
00:00:00:022  4  020001
...
00:00:00:030  7  201001
...
00:00:00:054  4  020002
...
00:00:00:064  7  201002
...
                            //BS4 Processor out
...
00:00:00:024  9  020001
...
00:00:00:028  0  201001
...
00:00:00:056  9  020002
...
00:00:00:060  0  201002
...
                            //UE2 Processor Out
...
00:00:00:026  4  201001
...
00:00:00:058  4  201002
...
```

Figure 6. UE communication in normal mode

```
//Time        Port value
...
00:00:00:132  0  103160 // From UE to its Serving BS
00:00:00:170  0  113160 // From UE to its Serving BS
...
```

Figure 7. UE to BS message

After receiving such a message from a UE, if it is possible the serving BS will try to set up a CoMP coordination set of BSs to enable the UE to operate in CoMP mode. To achieve this, the serving BS defines an interference message for the other BSs such that their signal can be sensed by the given UE. Then it sends these messages to the corresponding BSs. Figure 8 reveals a sample of this message type.

```
...
00:00:00:174 6 115601 //To other BS
00:00:00:174 1 115101 //To other BS
...
```

Figure 8. BS to BS message

Once the CoMP session has been established, the serving BS sends the scheduled data packets to the scheduled CoMP UE and the other BSs in the CoMP coordination set will send their packets simultaneously for the same scheduled UE (Figure 9). This approach will increase signal strength at the UE.

```
//Serving BS
...
00:00:00:178 6 201004 //To other BS
00:00:00:178 1 201004 //To other BS
00:00:00:180 7 201004 //To UE
...
//Other BS in coordination set
...
00:00:00:180 9 201004 //To UE
...
//Other BS in coordination set
...
00:00:00:180 9 201004 //To UE
...
```

Figure 9. BS to UE message

For the case of coordinated scheduling, the same events happen and the UE sends a control message (i.e. CSI information) to the serving BS. According to received message the serving BS ascertains the UE status and the channel information. As can be seen in Figure 10, after the serving BS processes the received message from the UE it can create a coordination set with the other BSs for which the UE senses their signal strength as being strong enough.

```
//UE Output
...
00:00:00:430 0 113610//To Serving BS
...
//Serving BS Input
...
00:00:00:432 In 113610
...
//Serving BS Output
...
00:00:00:438 1 114010 //To other BS
00:00:00:438 6 114060 //To other BS
...
//Other BS in coordination set Input
00:00:00:438 0 114010
...
//Other BS in coordination set Input
00:00:00:438 0 114060
...
```

Figure 10. Messaging to reduce interference level

Then the serving BS will send the interference cancellation message to the other BSs in coordination set. The CoMP scheduling continues while a UE remains in a common area which is covered by the BSs of the CoMP coordination set, so that the UE, can benefit from high data rate and reduced interference.

6. Conclusion

DEVS as a formal modeling and simulation methodology that provides a hierarchal and easy-to-modify framework for which the validity of the system is guaranteed. In this work, a DEVS-based model was introduced for CoMP approaches in LTE-Advanced mobile networks. We have used the DEVS model specifications for network components and the CD++ toolkit has been used for its implementation. The simulation results confirm the fact that by using CoMP techniques it is possible to control and reduce inter cell interference. This approach will lead to improvements in mobile network performance. At same time users of such networks will experience consistent quality of service regardless of their distance from base station in the cell center.

Going forward there are a number of challenges that need to be addressed to optimize the performance of CoMP. These issues include the signaling overhead due to the setting up of the CoMP coordination, backhaul delay, overhead and channel status estimation.

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