Final Project Report

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

SYSC 5104
Discrete Event Modeling and Simulation

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Abstract

Considering the ever increasing bandwidth demand of the users in cellular networks, there has been lots of effort to propose new standards to support users' requirements and increase their performance in mobile networks. One of the promising mobile communication standards for the Fourth Generation (4G) cellular systems is Long Term Evolution Advanced (LTE-Advanced). This technology try to provide high data rates and improve the users' quality of service by using a number of technologies including Coordinated Multipoint (CoMP). CoMP refers to a number of geographically separated transmission points which dynamically coordinate to support joint scheduling and transmissions in order to improve system performance. In this report Discrete Event System Specification (DEVS) formalism has been used to model a mobile network and test two approaches in CoMP: Coordinated Scheduling/Beamforming and Joint Processing.

1. Introduction

The global use of radio spectrum required to be managed by an international organization for better deployment and to facilitate radio spectrum usage around the world. The International Telecommunication Union is a specialized agency of the United Nations which is responsible for information and communication technologies. The ITU is active in various areas such as broadband Internet, latest-generation wireless technologies, satellite-based meteorology, Internet access and next-generation networks. In case of radio spectrum, the ITU coordinates the shared global use of it. It is also works on improving telecommunication infrastructure and worldwide telecommunication standards. The latter work led to different mobile telecommunication generation standards to fulfill users' requirements in different periods.

1.1. First Generation of Mobile Telecommunication

In 1978, the first commercial deployment of the first generation (1G) mobile cellular networks was born. Different analog telecommunication standards such as Advanced Mobile Phone System (AMPS), Nordic Mobile Telephony (NMT) and Total Access Communication System (TACS) were developed based on 1G specification.

AMPS is an analog mobile phone system standard developed by Bell Labs. It was introduced in the Chicago in 1978. For almost twenty years it was the primary analog mobile phone system in North America. AMPS uses FM modulation and Frequency Division Multiple Access (FDMA) as a channel access method. To avoid interference between cells, each cell uses a different set of channels than neighboring cells. A clear drawback is the significantly reduced number of channels available at each cell in real-world systems.

NMT was the first international mobile communication system. This fully automatic cellular phone system was tested in 1976 and finally it was introduced in Nordic countries in 1981. It has two variants: NMT450 and NMT900 in which the numbers indicate the frequency bands. NMT uses full duplex transmission and frequency modulation (FM). There are two important issues regarding NMT. The first one is roaming concept which was introduced in this standard. Roaming is defined as giving a service to users travel outside their local operators' coverage. The second one is the free and open specifications of NMT which led to pushing the hardware price down by allowing many companies to produce NMT required hardware.

TACS uses FM modulation and FDMA as a channel access method too. But it uses more frequency bandwidth in compare to AMPS. This system used in New York for the first time in 1984. By injecting some changes to TACS standard such as increasing frequency bandwidth, E-TACS was considered as the extended version of TACS which was born in 1988.

In general, characteristics of the first generation of mobile telecommunication can be listed as follow: limited capacity, limited service, low voice quality, heavy and bulky equipment, analog transmission technique and crosstalk which may cause interference among frequencies and disrupting the transmission.

1.2. Second Generation of Mobile Telecommunication

To answer the ever increasing requirements of users in mobile networks and also to improve the overall performance and quality of service the second generation (2G) of mobile telecommunication standards systems was developed and it was based on digital technology. This characteristic was the main difference between two succeeding mobile telephone systems, 1G and 2G.

There were two important reasons which caused to bring digital transmission in mobile communication. The first one was the need to improve transmission quality, system capacity, and coverage. The second one was further advances in semiconductor technology and microwave devices during those times.

Two famous standards bases on 2G specifications are Digital Advanced Mobile Phone System (DAMPS) and Global System for Communication Mobile (GSM). The former tried to cover AMPS weaknesses such as poor security system and it was introduced in 1990. It was a digital system and also it was a backward compatible system with analog cellular networks. The latter was the result of agreement among seventeen European countries accepted to develop and deploy a common cellular telephone system to support the requirements of their users in any time or location across Europe. In 1991 this system used in noncommercial form and by end of same year it was used as commercial mobile system.

This family of standards continued their improvement in GSM mobile communication technology by developing High Speed Circuit Switched Data (HSCSD) and General Packet Radio Services (GPRS). HSCSD is a circuit switching data service using several GSM radio channels simultaneously to achieve higher data transmission rate. GPRS was introduced in GSM by adding packet switching protocols in to GSM in 1990. Some of the benefits of GPRS network are as following: more efficient usage of radio resources, less cost, less delay in compare to GSM standard and using packet switching which was the first step to reach to the third generation.

1.3. Third Generation of Mobile Telecommunication

Third Generation (3G) of mobile telecommunications is a set of standards and protocols introduced for mobile telecommunication and required devices that comply with the International Mobile Telecommunications-2000 (IMT-2000) specifications by the International Telecommunication Union. To do so, the third generation partnership project (3GPP) was formed by standards developing organizations from all regions of the world to cease the parallel 3G activities were going on in different parts of the world and developing required standards. The 3GPP specification work is done in Technical Specification Groups (TSGs) and Working Groups (WGs). The scope of 3GPP when it was formed in 1998 was to produce global specifications for a 3G mobile system based on an evolved GSM core network. The work in 3GPP is carried out with relevant ITU recommendations in mind and the result of the work is also submitted to ITU. The 3GPP documents are divided into releases, where each release has a set of features added compared to the previous release. The specifications of all releases can be updated after each set of TSG meetings, which occur 4 times a year. Figure 1 reveals some important issues of each of these releases.

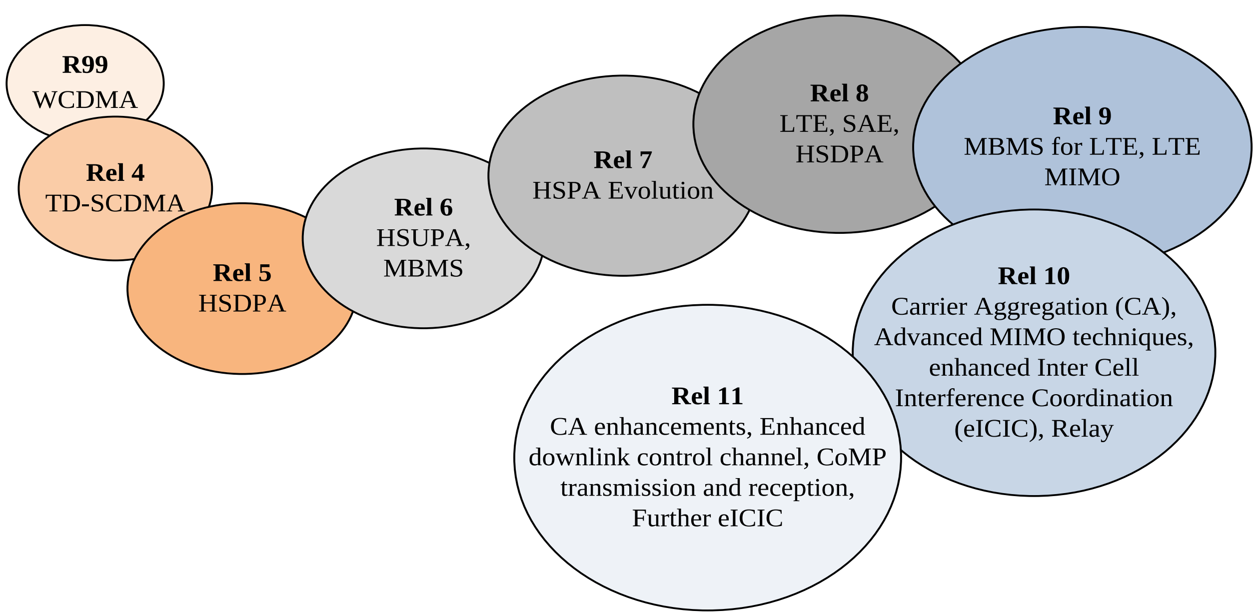

Figure 1: Key enhancements in 3GPP's releases

One of the important standards in 3G family is Universal Mobile Telecommunications System (UMTS) which is the successor to GSM. UMTS uses Wideband Code Division Multiple Access (WCDMA) radio access technology to support and prepare greater spectral efficiency and bandwidth to mobile network operators and this is its major difference with GSM/GPRS networks in which time division multiple access (TDMA) and frequency division multiple access (FDMA) are used as access methods [1,2,3]. Wideband Code Division Multiple Access (WCDMA) is a spread-spectrum modulation technique. This means that channels bandwidth is much greater than that of the data to be transferred. In this method instead of using assigned time slot like TDMA or assigned frequency band like FDMA the modulation technique encodes each channel in such a way that a decoder, knowing the code, can pick out the wanted signal from other signals using the same band [1,3].

Another important standard in this family is High Speed Packet Access (HSPA) which is based on UMTS/WCDMA standard. The introduction of High-Speed downlink Packet Access (HSDPA) in Release 5 of the 3GPP/WCDMA specifications was the first step in this evolution. For the most WCDMA networks just a software update is enough to upgrade the system to HSDPA. The second step was to upgrade the uplink which was done by introduction of High-Speed Uplink Packet Access (HSUPA) in Release 6 of the 3GPP/WCDMA specifications. This step is usually only a software update. The combination of HSDPA and HSUPA are often referred to as HSPA or in other word HSPA is the terminology used when both HSDPA and HSUPA technologies are deployed on a network [1,4,5].

As it can be seen in Figure 1, Multimedia Broadcast Multicast Services (MBMS) was introduced in release 6 to provide broadcast services into WCDMA. MBMS is a point-to-multipoint interface specification to support delivery of both broadcast and multicast services within a cell and the core network. When numbers of users in a cell wait for same data this service provide broadcast transmission instead transmitting the same information individually to each of the users. Mobile TV, radio broadcasting, file delivery and emergency alerts are some of target applications for this service. In release 7, Multiple-Input and Multiple-Output (MIMI) was introduced to improve the peak data rates through multi-stream transmission.

Maybe we can say that the most important standard in this family of mobile networks standards is Long Term Evolution (LTE). It is based on the GSM/EDGE and UMTS/HSPA network technologies, increasing the capacity and speed and it should support for inter operation and coexistence with WCDMA, HSPA and GSM standards. LTE assumes a full Internet Protocol (IP) network architecture (supporting both IPv4 and IPv6) and is designed to support voice in the packet domain. Also core network has been upgraded to support the new packet data capabilities provided by the LTE radio interfaces. The work on specifying the core network is known as System Architecture Evolution (SAE). LTE uses Orthogonal Frequency Division Multiplex (OFDM) as the signal bearer and the associated access method. 3GPP develops and specifies LTE standard in its Release 8 document series. There are minor enhancements described in Release 9. Figure 2 illustrates the 3GPP family evolution timing.

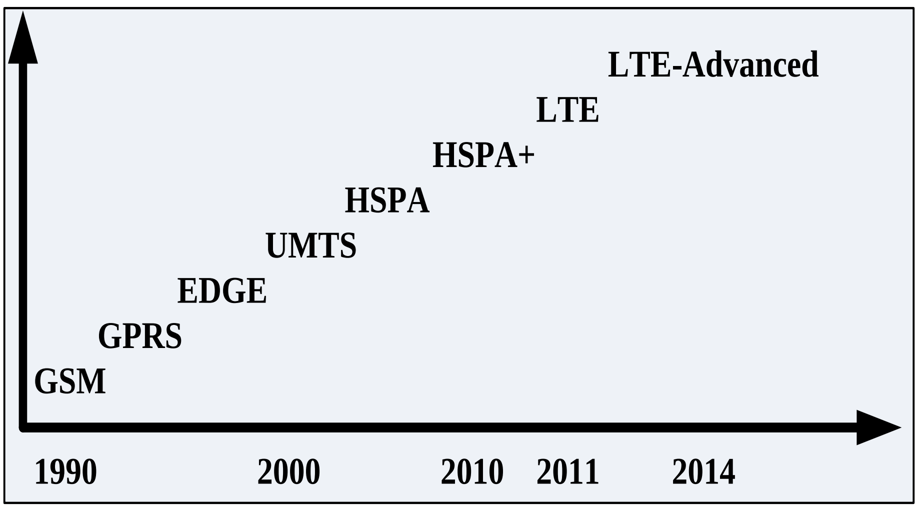

Figure 2: 3GPP family evolution timing

1.4. Fourth Generation of Mobile Telecommunication

The successor of the third generation (3G) standards in the telecommunication is the Fourth Generation of mobile Telecommunication (IMT-Advanced). LTE-advanced and WiMAX-advanced are the two 4G candidate systems that are commercially deployed. LTE-Advanced was standardized by 3GPP in Release 10 and Release 11 in response to next generation of wireless technology (IMT-Advanced). LTE-Advanced is an evolution of LTE which was specified in Release 8 and 9. According to definition this system will be backward compatible, as well as forward compatible with LTE. This means that LTE devices will work on LTE-Advanced networks and same thing should happen for LTE-Advanced devices in LTE network. Some of the other main headlines for LTE-Advanced are as followings:

- Peak data rates in downlink and uplinks are 1 Gbps and 500 Mbps in order.
- Its spectrum efficiency is three times greater than LTE.
- Its cell edge user throughput should be twice of LTE.
- In case of average user throughput it should be three times of LTE.
- Peak spectrum efficiency in downlink and in uplink is 30 bps/Hz and 15 bps/Hz in order.
- In term of mobility it is same to LTE.

Table 1 summarized the 3GPP family characteristics.

	WCDMA (UMTS)	HSPA	HSPA+	LTE	LTE-Advanced
Max DL Speed (bps)	384 K	14 M	28 M	100 M	1 G
Max UL Speed (bps)	128 K	5.7 M	11 M	50 M	500 M
Latency (round trip time)	150 ms	100 ms	50 ms	10 ms	< 5 ms
Access Methodology	CDMA	CDMA	CDMA	OFDM	OFDM
3GPP Release	Rel 99/4	Rel 5/6	Rel 7	Rel 8/9	Rel 10/11

Table 1: 3GPP family characteristics

2. Background

To overcome transmission barriers such as Inter-Cell Interference (ICI) and support the high data rates and meet the IMT-Advanced requirements a number of technologies includes advanced Multiple Input Multiple Output (MIMO), Orthogonal Frequency Division Multiplexing (OFDM), wireless relays, Enhanced Inter-Cell Interference Coordination (eICIC), Carrier Aggregation (CA) and Coordinated Multipoint (CoMP) are used in LTE-Advanced [6].

2.1. Multiple Input Multiple Output

Generally in wireless systems we have four types of antenna configuration including Single Input Single Output (SISO), Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO) and Multiple Input Multiple Output (MIMO). MIMO is the use of multiple antennas at both the transmitter and receiver to increase communication performance without additional bandwidth or increased transmit power. It is important to mention that the terms input and output refer to the radio channel carrying the signal, not to the devices having antennas. This can be used to achieve a diversity gain (the increase in signal-to-interference ratio) and thereby improves the link reliability (reduced fading). MIMO is an important part of modern wireless communication standards. In LTE-Advanced networks a BS can operate in one of MIMO modes which are: Single-User MIMO, Multi-User MIMO and Cooperative MIMO (Figure 3). In SU-MIMO a point to point transmission of data employed for one multi antenna UE. MU-MIMO exploits the availability of multiple independent UEs in order to improve the communication capabilities of each individual UE. Cooperative MIMO methods tries to increase cell edge user performance by enabling coordination among different BSs and it is known as Coordinated Multipoint which will be discussed in followings sections.

There are different types of approaches in term of MIMO including spatial diversity, beamforming, spatial multiplexing and interference cancellation. In general we can say that the main ideas to use them are to increase coverage area, data rate and system reliability and also to decreases the required transmit power.

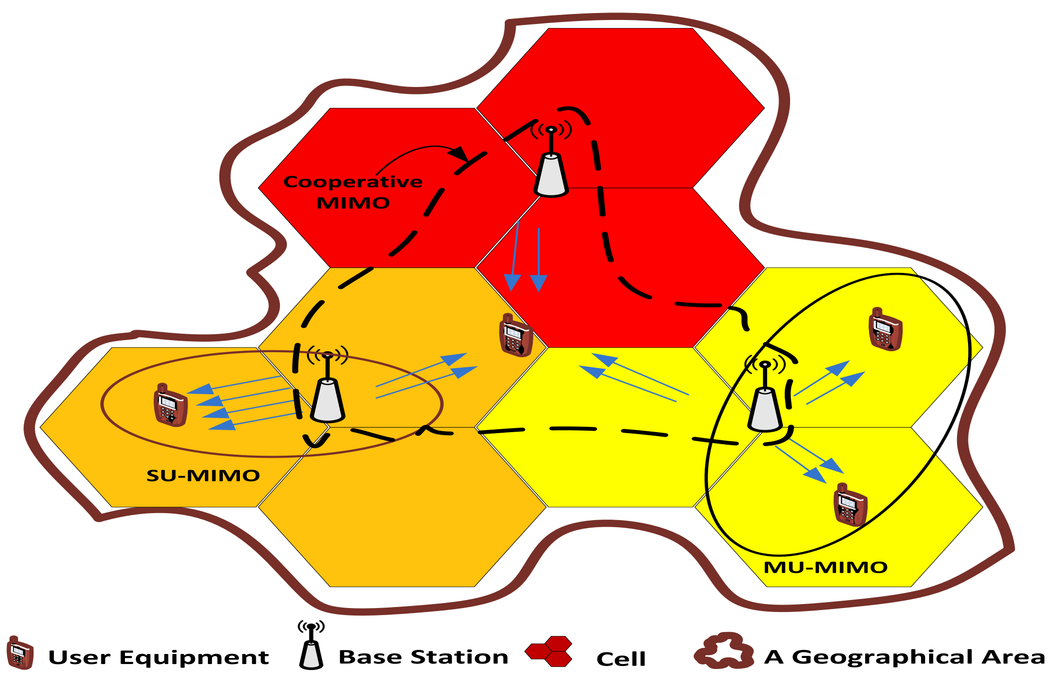

Figure 3: Single-User MIMO mode and Multi-User MIMO mode

Spatial Diversity provides multiple independent channels between the transmitter and the receiver and its performance is related to the channels' status. Beamforming techniques try to increase the desired signal energy while suppressing or nulling, interfering signal. In spatial multiplexing multiple data streams transmitted simultaneously to increase capacity. Interference cancellation (IC) is suitable for UEs who are experiencing low Signal-to-Interference-and-Noise Ratio (SINR) like Cell edge UEs. In this technique feedback from UEs is required as same as BSs corporation to let the multiple antennas at the transmitter to null interference to other UEs.

2.2. Orthogonal Frequency Division Multiplexing

OFDM is a member of family of transmission schemes called multi-carrier modulations. The basic idea in this class is to dividing a given high-bit-rate data stream into several parallel lower bit-rate streams and modulating each stream on separate carrier often called subcarriers.

LTE-Advanced same as LTE uses Orthogonal Frequency Division Multiplex (OFDM) as the signal bearer and the associated access method. This method has many advantages such as robustness to multipath fading and interference. The other important advantage of OFDM is the fact that it can be used in both FDD and TDD formats. OFDM is a kind of transmission that uses a large number of close spaced carriers that are modulated with low rate data. UEs are dynamically assigned sub-carriers (FDMA) in different time slots (TDMA).There is possibility for interference between these signals in normal situation, but this problem was solved in OFDM by making the signals orthogonal to each another, hence there is no mutual interference. Considering the advantages of OFDM, it is the natural choices for the LTE cellular standard access method. But there are different requirement between the downlink and the uplink and as a result the actual implementation of the technology will be different between them.

2.3. Wireless Relay

Among all different aspects in mobile communication there are two factors which are more important than the others. These factors are coverage and data rates. The main goal of lots of research in this field is to increase both of them in reasonable ways. In the other side BSs have important roles in LTE-Advanced networks and they functionality has been improved during the years. In a same time their costs increased too so their price can be consider as a limitation factor for coverage extension. If we put the both above issues together it is clear that it would be helpful if we can have equipment that can extend cell coverage and improve cell edge performance and in same time it has lower price in compare to BSs. Wireless relays are proper option to solve such a problem. The Relay Node (RN) is a radio device that can help to conveying the data from BSs to UEs and vice versa. Generally, these RN can be categorized in two classes. In one of them there are just simple passive repeaters that only forward analog signals. The other one includes active RN which can communicate with other network elements like BSs, UEs or pother RNs. Considering the bandwidth RNs use they have been divided in two types which were named inband and outband. In case of the former both BS-RN and RN-UE links share same bandwidth (carrier frequency). In the latter each of those links works in different bandwidth [7,8].

In release 10, two types of RN are described for LTE-Advanced networks. In type I, the RNs controlling their own cells and they have their own cell ID. So they have reverence signals and channel specifications. Both inband and outband RN can be used in this type. RN type II does not have a separate physical cell identity neither cell ID. This type of RNs is transparent to release 8 UEs in which UEs are not aware of the presence of a type II RN. In fact in this type RNs are low cost devices that operating inband.

2.4. Enhanced Inter Cell Interference Coordination

Homogeneous mobile networks consist of same type and same power class of base stations. On other hand to support the ever increasing mobile traffic demands different low power base stations with small size such as picocells or femtocells or even relays are being deployed to the cells to serve hot zones. This type of architecture is called as heterogeneous network. Figure 4 illustrates both types of networks [8,9].

Inter Cell Interference (ICI) is the major bottleneck for the cellular networks performance [10]. This problem affects cell edge users' performance dramatically. It is also preventing mobile network standards coming close to their theoretical rates [11]. In fact, ICI is the result of using same radio resources in different cell in an uncoordinated way [12]. In other word, if UEs in adjacent cells are served by using same radio resources then they will experience inter cell interference. Over the years to overcome these problems different types of techniques such as interference cancellation, interference coordination and interference randomization has been investigated [7,9,13,14]. Also according to some of categorization, all of these methods which try to deal with ICI are derived from two basic ideas: coordination of base stations to avoid interference and constructive exploitation of interference through coherent base station cooperation [11].

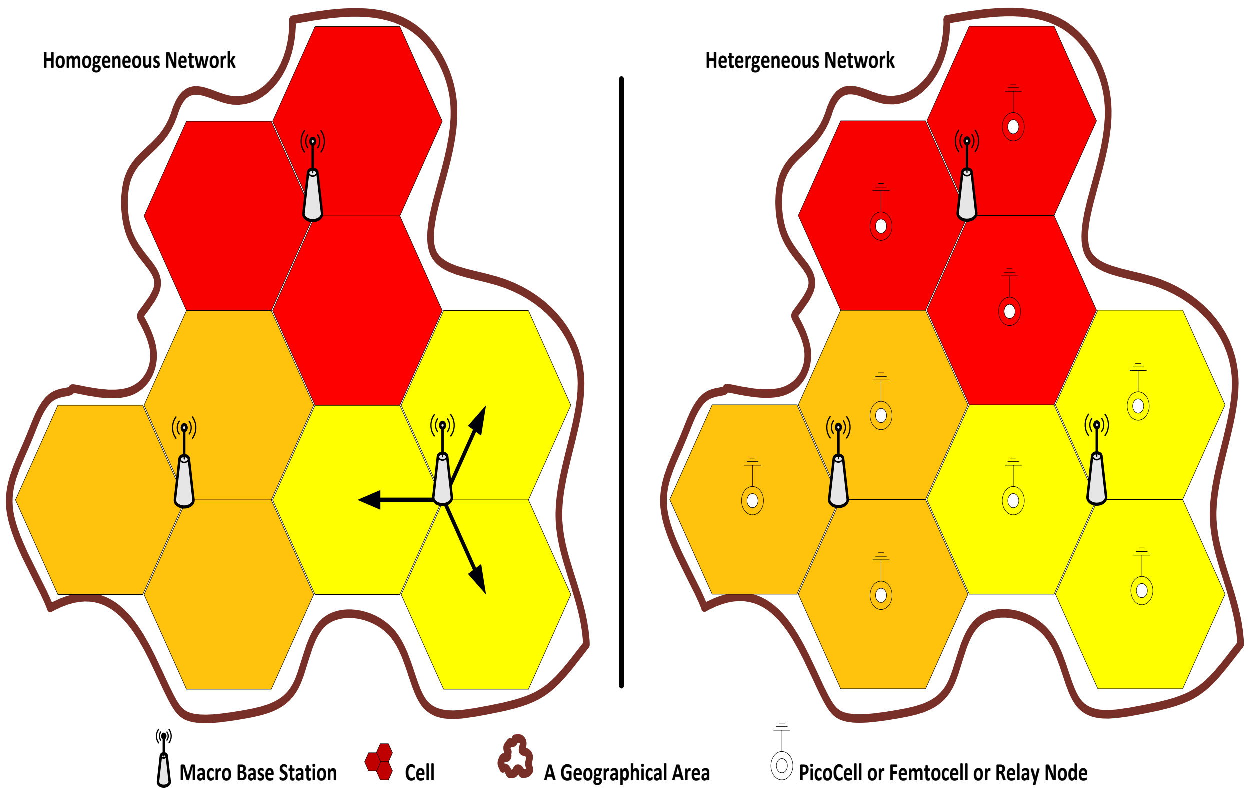

Figure 4: Homogenous and Heterogeneous Mobile Networks

Inter Cell Interference Coordination (ICIC) is provided by exchanging coordination message between base stations via a standardized interface named X2. ICIC prepare the scheduling information at a cell with information about the current or prospective interference situation at its neighbors. ICI problem is become even more complicated in case of heterogeneous networks due to a large number of heterogeneous cells that could exist in a certain area. In this case in certain situations, the signal from the serving cell could be much weaker than that from the interfering cells, which is referred to as dominant interference scenario [15]. Figure 5 reveals such a scenario between a macro base station and a femtocell.

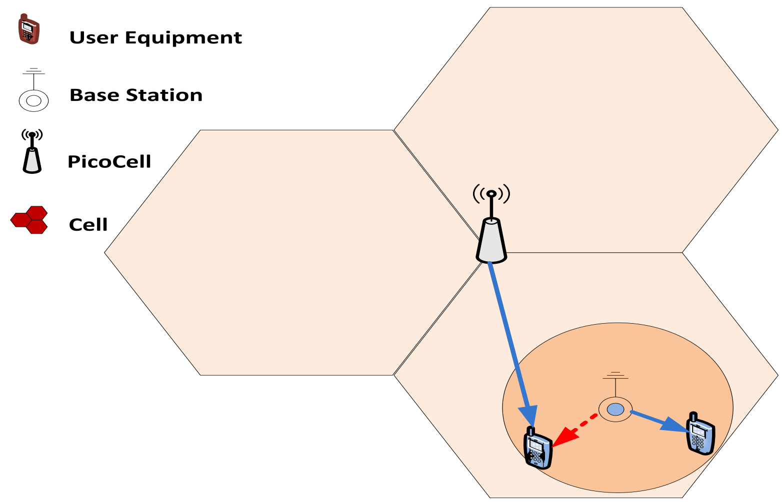

Figure 5: Dominant Interference Scenarios

The ICIC methods of the LTE release 8 and 9 do not consider dominant interference scenarios of heterogeneous networks. In order to solve such problems, the LTE-Advanced has been developing enhanced ICIC (eICIC) techniques. These techniques can be classified into three categories: time-domain techniques, frequency-domain techniques, and power control techniques. Table 2 demonstrates the characteristics of different elements of heterogeneous networks [7].

Element	Transmit Power (dBm)	Coverage	Backhaul
Macro cell	46	Few km	S1 interface
Picocell	23-30	< 1300 m	X2 interface
Femtocell	<23	< 50 m	Internet IP
Relay	30	300 m	Wireless

Table 2: Characteristics of different elements of heterogeneous networks heterogeneous networks

2.5. Carrier Aggregation

LTE-Advanced should provide high data rates for its users and one reasonable way to do such thing is to extend the transmission bandwidth. LTE-Advanced can increase allocated bandwidth up to 100 MHz (LTE spectrum is ranging from 1.4 MHz up to 20 MHz). To support extended bandwidth and keep backward compatibility with LTE user, carrier aggregation approach is used in LTE-Advanced networks. In this technique multiple component carriers are aggregated to provide desired bandwidth for LTE-Advanced users. Figure 6 shows a simple carrier aggregation. Remember that to an LTE Release 8 UEs, each component carrier will appear as an LTE carrier, while an LTE-Advanced UEs can exploit the total aggregated bandwidth [16].

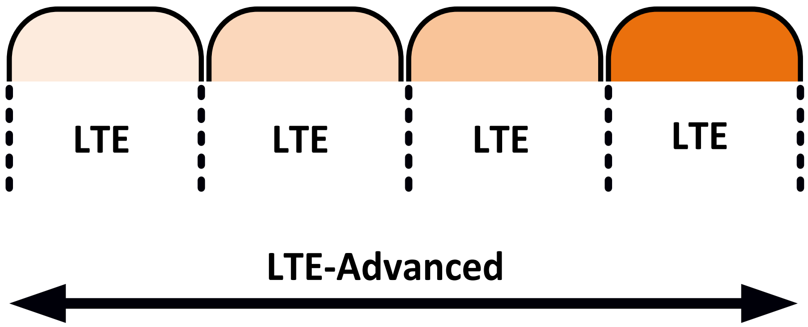

Figure 6: Sample of carrier aggregation in continues bandwidth

Carrier aggregation of none continuous spectrums are possible too. In fact from a baseband perspective, there is no difference if the component carriers are contiguous in frequency or not. But the problem rise up in implementation and its implementation is challenging. In LTE Advanced, different component carriers are aggregated above the MAC layer which means that hybrid-ARQ retransmissions are performed independently per component carrier.

2.6. Coordinated Multipoint

As it was mentioned CoMP is a key technique in LTE-Advanced to deal with interference problem. CoMP refers to a number of geographically separated base stations (BSs) dynamically coordinate to support joint scheduling and transmissions, as well as proving joint processing of the received signals in order to improve system performance. In fact these BSs form coordination set and the main idea is to manage interference to enhance UEs' performance especially for the cell edge users [16]. It is clear that data rates are relatively easy to maintain close to the BS but as distances between UE and BS increase it is more difficult to maintain the high data rate. The most challenging situation occurs when UE is close to cell edge. In this case beside the lower signal strength (because of the distance between UE and base station) interference level from neighboring BSs is higher as the UE will be closer to them. By using this approach (coordinating and combining signals from multiple antennas) it will be possible for mobile users to enjoy high quality and consistent performance when they require high-bandwidth services for different range of applications. The important point is that this feasibility is supported for users regardless of their distance from cell center. In fact CoMP will increase data transmission rates and ensure 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 sending scheduling decisions, hybrid ARQ feedback, channel state information (CSI) and other control information for each other [13]. BSs share the received messages from their UEs with other BSs in coordination set through standard interfaces which is called X2.

Considering the way that these control information is made available at the different transmission point, 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. Generally, UEs estimate channel status and then it feedbacks these information for its serving cell. Once the serving cell receives this information from its UEs, it forwards this information to the central unit that is responsible for scheduling operations. After computing those parameters central unit send the results for coordinated BSs in coordination set. The main challenge in this architecture is about latency requirements to support effective information exchange. Also it has more overhead on backhaul. In the distributed CoMP transmission approach, the UE send back the channel status to all of the BSs in coordination set. So each BS receives all the feedbacks even those related to other BSs in coordination set and then it can perform scheduling operation independently. It is worth to mention 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. A serious problem in this kind of architecture is handling the errors on same feedback information on the different feedback links [12,17,18,19].

There are two schemas for CoMP in LTE-Advanced with respect to the way the data and scheduling information shared among BSs: Coordinated scheduling/Beamforming and Joint Processing (Figure 7).

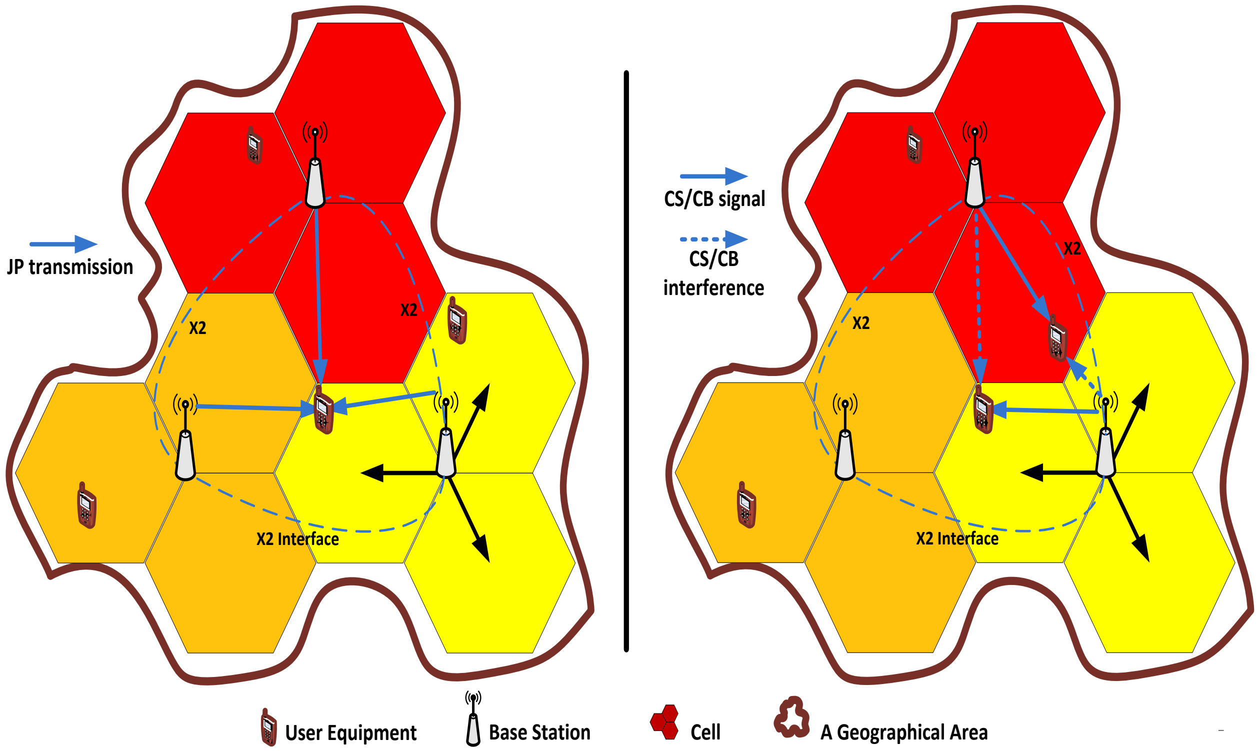

Figure 7: JP transmission and Coordinated Scheduling/Beamforming in LTE-Advanced

In the latter BSs in the coordination set share the data as well as channel state information and scheduling information with other BSs. In the former data exchange is not required and BSs just need to share channel state information and scheduling information. In other word in the joint processing scheme data to a single UE is transmitted from BSs in coordination set simultaneously. This increases the signal quality at UE side and also decreases the interference level. But in same time the amount of data needs to be exchanged over the backhaul is very large. In the coordinated scheduling/beamforming each UE is served by a one of the BSs in coordination set (serving BS) and the scheduling decisions are selected in a way to control interference among BSs in coordination set. Therefore in this case BSs just need to share scheduling information and UE data do not need to be conveyed to all BSs in coordination set since there is only one serving BSs for one particular UE [6,12,13,17,20].

There is another approach in this area which is considered as a kind of joint processing technique and it is called Dynamic Cell Selection. Same as normal joint processing technique here data are transmitted from several BSs in coordination set but this transmission does not occur simultaneously. In fact it uses fast BS selection approaches and only one of the BSs from coordination set transmit data at each time. Figure 8 shows how this technique works.

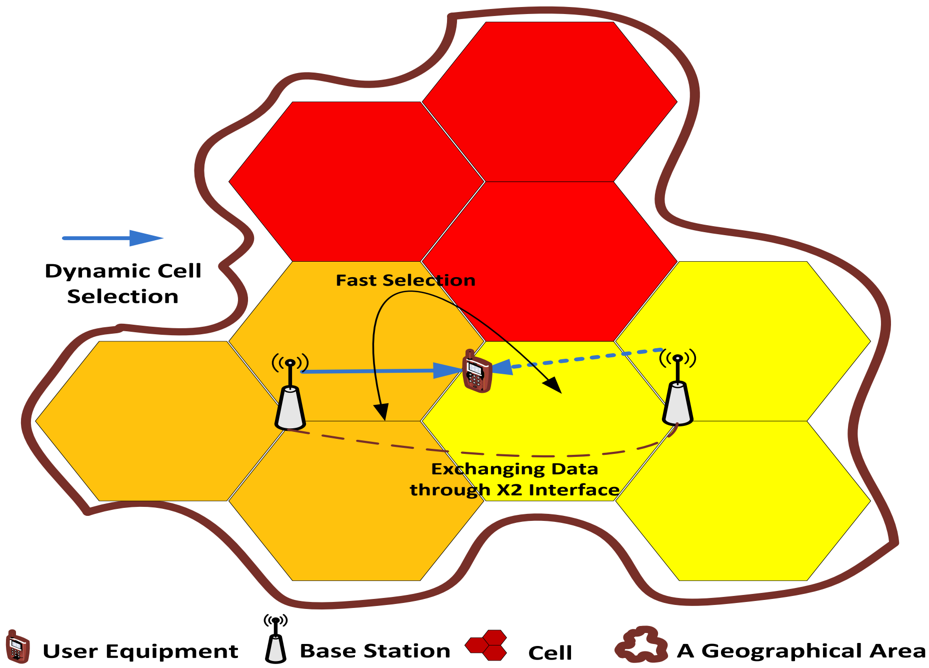

Figure 8: Dynamic Cell Selection in LTE-Advanced

In general, both users and network operators benefit from CoMP advantages. Some of these approaches have been listed in following [21,22]:

- Makes better utilization of network: CoMP provide connections to several base stations therefore traffic packets can be passed through least loaded base station.
- Provides enhanced reception performance: By using several cell sites for each connection, overall reception will be increased and the number of lost calls should be decreased.
- Multiple site reception increases received power: Overall received power at the handset to be increased by using the joint reception from multiple base stations or sites.
- Interference reduction: By using specialized combining techniques it is possible to utilize the interference constructively rather than destructively, thereby reducing interference levels.

3. Modeling

Discrete Event Systems Specification (DEVS) is a formal frame work 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 continues 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. Also a coupled model itself can be composed of atomic or coupled models [23]. A DEVS atomic model is formally specified by [23]:

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

Where

$\boldsymbol{X} = \{(p, v) \mid p \in IPorts, v \in X_p\}$ 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.

$\boldsymbol{Y} = \{(p, v) \mid p \in OPorts, v \in Y_p\}$ 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.

$\boldsymbol{S}$ is the set of sequential states.

$\boldsymbol{\delta_{int}}: S \rightarrow S$ is the internal state transition function.

$\boldsymbol{\delta_{ext}}: Q \times X \rightarrow S$ is the set of external transition function where $Q = \{(s, e) \mid s \in S, 0 \leq e \leq ta(s)\}$ and e is the elapsed time since last transition function.

$\boldsymbol{\lambda} = S \rightarrow Y$ is the output function.

$\boldsymbol{ta}: S \rightarrow R_0^+ \cup \infty$ is the time advance function.

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 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 desired output ports and then it performs internal transition function to determines the new state by $\delta_{int}(s)$. This situation describes how an internal transition occurs. On the other hand, state transition can also happen due to 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 surrent 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 defined interval in definition. A state with $ta(s) = 0$ is called transient state which will lead to an instantaneous internal transition. Also if $ta(s) = \infty$ the state is said to be passive in which the system will remain in this state until receiving an external event. It is worth to mention that the last situation can be used as termination condition.

As it was mentioned a DEVS coupled model can be composed of several atomic or coupled submodels. It is formally defined by:

$$\boldsymbol{CM} = <\boldsymbol{X}, \boldsymbol{Y}, \boldsymbol{D}, \{\boldsymbol{M_d} \vdots \boldsymbol{d} \in \boldsymbol{D}\}, \boldsymbol{EIC}, \boldsymbol{EOC}, \boldsymbol{IC}, \boldsymbol{select}>$$

Where,

$\boldsymbol{X} = \{(p, v) \mid p \in IPorts, v \in X_p\}$ 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.

$\boldsymbol{Y} = \{(p, v) \mid p \in OPorts, v \in Y_p\}$ 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.

$\boldsymbol{D}$ is the set of the component names and for each $d \in$ D.

$\boldsymbol{M_d}$ is a DEVS basic (i.e., atomic or coupled) model;

$\boldsymbol{EIC}$ is the set of external input couplings,

$$EIC \subseteq \{ \left((self, in_{self}), (j, in_j)\right) \mid in_{self} \in IPorts, j \in D, in_j \in IPorts_j\}$$

$\boldsymbol{EOC}$ is the set of external output couplings,

$$EOC \subseteq \{ \left((i, out_i), (self, out_{self})\right) \mid out_{self} \in OPorts, j \in D, out_i \in OPorts_i\}$$

$\boldsymbol{IC}$ is the set of internal couplings

$$IC \subseteq \{ \left((i, out_i), (j, in_j)\right) \mid i, j \in D out_i \in OPorts_i, in_j \in IPorts_j\}$$

$\boldsymbol{select}$ is the tiebreaker function, where $select \subseteq D \rightarrow D$, such that, for any nonempty subset E, $select(E) \in E$.

3.1. Modeling of a Mobile Network

As it has been shown in Figure 4, mobile networks or cellular networks are kind of radio networks distributed over land areas. Each of these land areas known as a cell. Each cell has at least one fixed transceiver called base station. These cells support radio coverage over a geographic area by joining together and each of them include at least one BS and a number of users which is ≥ 0 . Figure 9 demonstrates a simplified DEVS model hierarchy for these concepts.

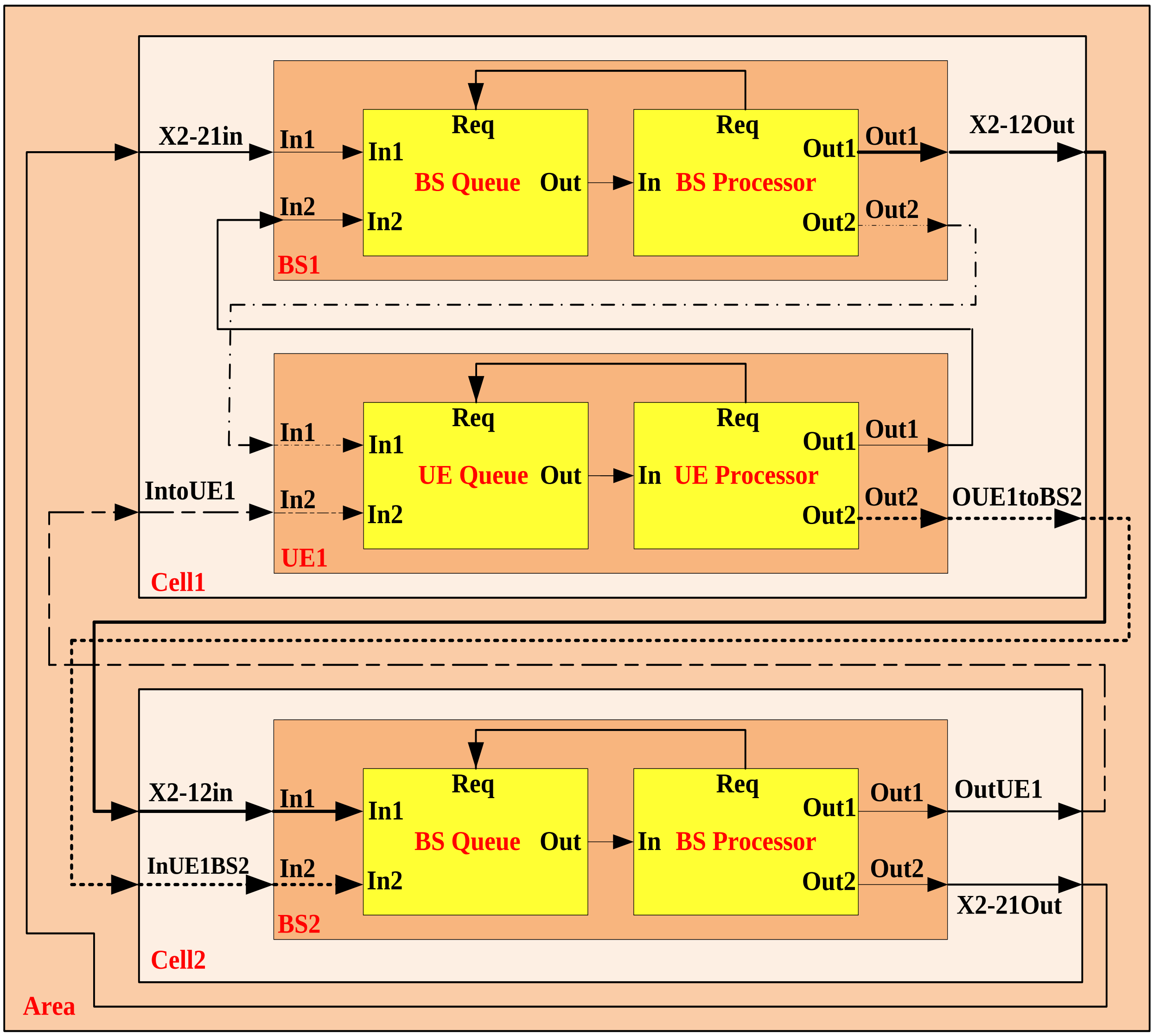

Figure 9: Simplified DEVS model hierarchy for mobile network model

The model in the top level includes an area which constructed of seven cells. Each cell has one BS and it can have zero or one or more than one UEs. Area, Cells, BSs and UEs are coupled model. Each of BSs and UEs consist of two atomic models including Processor and Queue.

Obviously UE's processor functionality is different from BS's Processor. In case of Queue there are both same. UEs are able to send or receive data packets to/from each other. Also they send control information such as CSI for BSs. Control packets include the base information for BSs. This information helps BS to follow UE's status. For example according to this information a serving BS can determine if a certain UE wants to work in normal mode or CoMP mode and if it wants to work in CoMP mode which BSs are in coordination set therefore it has to send data and control information for those BSs. Also base on these control packets a BS can understand that a UE want to move from one cell to another cell or even a UE wants to leave the Area or not. BSs should handover both data packet and control packets to other BSs. In case of data packet they forward the packets according to their destination. Control packets depend on the information they carry can be distributed between BSs in a same coordination set or into the entire network. An example for latter case can be a UE movement from one cell to another cell. 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 mobile network will understand that a certain UE change its serving cell and they will update their routing tables. In results if they want to forward a packet for that UE they will send it for new address. We mention that in previous sections that BSs communicate with each other through X2 interfaces and base on above description it is clear that X2 interface characteristic can has a huge effect on overall network performance.

DEVS formal definition of a BS's Queue is generally as same as UE's Queue but there is difference in input set. DEVS formal definition of a UE Queue, UE Processor and BS Processor are as follows:

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

X: Input ports equal to number of BSs. Also there is (Req, 1) which is used by Processor to show that it can accept new job.

Y: Output to Processor.

S: {Idle, Push, Pop}.

$\boldsymbol{\delta_{ext}}$: Receives messages from input ports and initiates appropriate state transition.

$\boldsymbol{\delta_{int}}$: Define state changes according to current state.

$\boldsymbol{\lambda}$: It will send out the first member of Queue for the Processor.

$\mathbf{t_a}$: time advanced function.

UEP = $< X, Y, S, \boldsymbol{\delta}_{\mathbf{int}}, \boldsymbol{\delta}_{\mathbf{ext}}, \boldsymbol{\lambda}, \mathbf{t_a} >$

X: Input port from Queue.

Y: Output equal to number of BSs and also a Request port.

S: {AskNewTask, Idle, SendPack, RecPack, RecACK, UEMode}.

$\boldsymbol{\delta}_{\mathbf{ext}}$: Receives messages from input port and initiates appropriate state transition.

$\boldsymbol{\delta}_{\mathbf{int}}$: Define state changes according to current state.

$\boldsymbol{\lambda}$: It will send out a new generated packet or ACK for a received packet or control information for serving BS (if this UE is in CoMP it will send control information for coordination set).

$\mathbf{t_a}$: time advanced function.

BSP = $< X, Y, S, \boldsymbol{\delta}_{\mathbf{int}}, \boldsymbol{\delta}_{\mathbf{ext}}, \boldsymbol{\lambda}, \mathbf{t_a} >$

X: Input port come from BS's Queue output.

Y: Output ports are equal to number of UEs and neighboring BSs. Also there is a Request port.

S: {AskNewTask, Idle, SetBS, SetUE, Normal}.

$\boldsymbol{\delta}_{\mathbf{ext}}$: Receives messages from input port and initiates appropriate state transition.

$\boldsymbol{\delta}_{\mathbf{int}}$: Define state changes according to current state.

$\boldsymbol{\lambda}$: It will send out (forward) received data packets or their ACK packets toward their destination. Also It will send control message for neighboring BSs and its UEs if it is required.

$\mathbf{t_a}$: time advanced function.

Figure 10 represents the GGAD state diagram of UE and BS Processors. DEVS formal definition of a UE, BS, Cell and Area as a coupled model are as follows:

$\boldsymbol{UE} = < \boldsymbol{X}, \boldsymbol{Y}, \boldsymbol{D}, \{\boldsymbol{M_d} : \boldsymbol{d} \in \boldsymbol{D}\}, \boldsymbol{EIC}, \boldsymbol{EOC}, \boldsymbol{IC}, \boldsymbol{select} >$

$\boldsymbol{X} = \{\text{Number of input ports is equal to number of BSs}\}$

$\boldsymbol{Y} = \{\text{Number f output ports is equal to number of BSs}\}$

$\boldsymbol{D} = \{UEQ, UEP\}$

$\boldsymbol{M_d} = \{M_{UEQ}, M_{UEP}\}$

$\boldsymbol{EIC} = \{(\,(self, In1), (\,UEQ, In1)\,)\,;\ (\,(self, In2), (\,UEQ, In2)\,)\,; \ldots\}$

$\boldsymbol{EOC} = \{(\,(\,UEP, Out1), (self, Out1)\,)\,;\ (\,(UEP, Out2), (self, Out2)\,)\,; \ldots\}$

$\boldsymbol{IC} = \{(\,(UEQ, Out), (\,UEP, In)\,)\,;\ \ (\,(UEP, Req), (UEQ, Req)\,)\}$

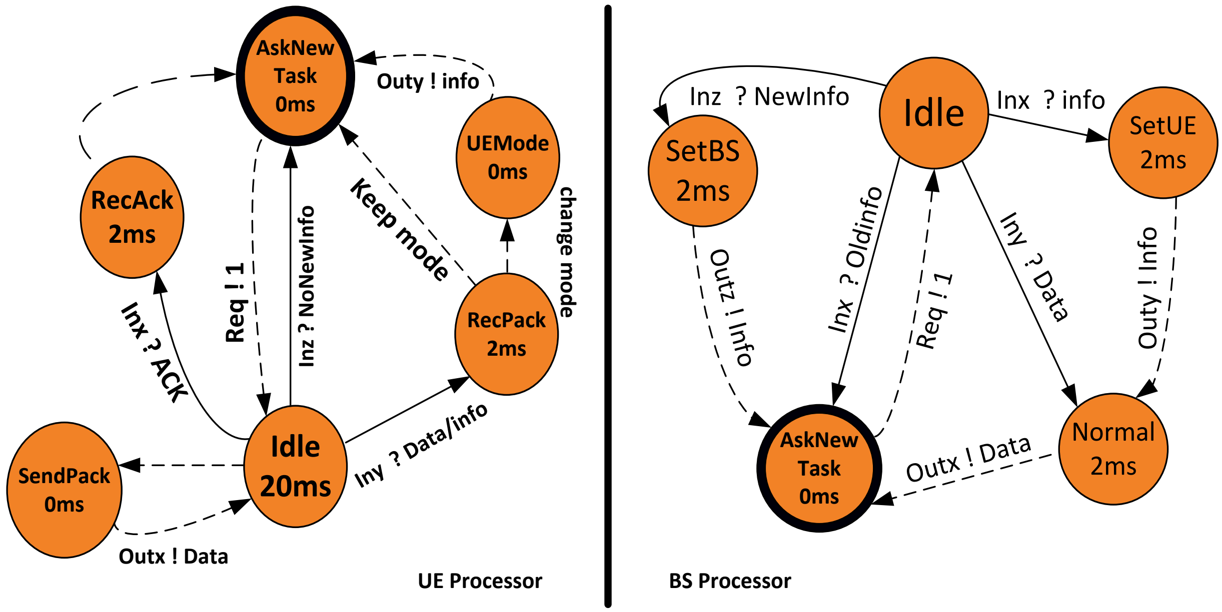

Figure 10: UE and BS processors GGAD diagram

$\boldsymbol{BS} = <\boldsymbol{X},\boldsymbol{Y},\boldsymbol{D},\{\boldsymbol{M_d} : \boldsymbol{d} \in \boldsymbol{D}\},\boldsymbol{EIC},\boldsymbol{EOC},\boldsymbol{IC},\boldsymbol{select}>$

$\boldsymbol{X} = \{\text{Number of input ports is equal to number of UEs + Number of neighboring BSs}\}$

$\boldsymbol{Y} = \{\text{Number of output ports is equal to number of UEs + Number of neighboring BSs}\}$

$\boldsymbol{D} = \{BSQ, BSP\}$

$\boldsymbol{M_d} = \{M_{BSQ}, M_{BSP}\}$

$\boldsymbol{EIC} = \{((self, In1),(BSQ, In1)) ; ((self, In2),(BSQ, In2)) ; \dots\}$

$\boldsymbol{EOC} = \{((BSP, Out1),(self, Out1)) ; ((BSP, Out2),(self, Out2)) ; \dots\}$

$\boldsymbol{IC} = \{((BSQ, Out),(BSP, In)) ; ((BSP, Req),(BSQ, Req))\}$

$\boldsymbol{Cell} = <\boldsymbol{X},\boldsymbol{Y},\boldsymbol{D},\{\boldsymbol{M_d} : \boldsymbol{d} \in \boldsymbol{D}\},\boldsymbol{EIC},\boldsymbol{EOC},\boldsymbol{IC},\boldsymbol{select}>$

$\boldsymbol{X} = \{\text{Number of input ports is equal to number of UEs + Number of neighboring Cells}\}$

$\boldsymbol{Y} = \{\text{Number of output ports is equal to number of UEs + Number of neighboring Cells}\}$

$\boldsymbol{D} = \{BS, and\ a\ set\ of\ number\ of\ UEs\ which\ is \geq 0\}$

$\boldsymbol{M_d} = \{M_{BS}, M_{UE_i} \mid \boldsymbol{i} \geq 1\}$

$\boldsymbol{EIC} = \{((self, In1),(BS, In1)) ; ((self, In2),(BS, In2)) ; \dots\}$

$\boldsymbol{EOC} = \{((BS, Out1),(self, Out1)) ; ((BS, Out2),(self, Out2)) ; \dots\}$

$\boldsymbol{IC} = \{connections\ between\ BS\ and\ UEs\}$

$\boldsymbol{Area} = < \boldsymbol{X}, \boldsymbol{Y}, \boldsymbol{D}, \{\boldsymbol{M_d} : \boldsymbol{d} \in \boldsymbol{D}\}, \boldsymbol{EIC}, \boldsymbol{EOC}, \boldsymbol{IC}, \boldsymbol{select} >$

$\boldsymbol{X} = \emptyset$

$\boldsymbol{Y} = \emptyset$

$\boldsymbol{D} = \{Cell_i \mid i = number\ of\ cells\}$

$\boldsymbol{M_d} = \{M_{Cell_i} \mid i = number\ of\ cells\}$

$\boldsymbol{EIC} = \emptyset$

$\boldsymbol{EOC} = \emptyset$

$\boldsymbol{IC} = \{connections\ between\ Cells\}$

3.2. Implementation in CD++

CD++ toolkit provides a simple framework for programming DEVS models. Model file is used for defining DEVS model hierarchical structure and coupling. Header file is used for defining atomic models as a class. Ports, variables and state definition of an atomic model can be found in this file. Definition of functions such as $\delta_{int}, \delta_{ext}$ and λ according to C++ programming language is done in CPP file by user. In this implementation of mobile network if we consider model hierarchical as a tree then the root of tree will be an area and the leaves of tree are atomic models. Model implementation was started by defining atomics models. Their functionality has been tested separately by using appropriate Event file. In next step, coupled model are defined according their structure which were described in previous sections and each of the coupled models were tested separately too. In the following it has been shown that how in the final step a model file was produced in order to define all the components and their interconnection.

```
[top]
components  :  Cell0  Cell1  Cell2  ...

Link  :  X2-01Out@Cell0  X2-01In@Cell1
Link  :  X2-02Out@Cell0  X2-02In@Cell2
...
Link  :  X2-10Out@Cell1  X2-10In@Cell0
Link  :  X2-20Out@Cell2  X2-20In@Cell0
...
```

```
[Cell0]
components  :  BS0  UE0  ...
in  :  X2-10In  X2-20In ...
in  :  InBS1ToUE0 ...
...
out : X2-01Out  X2-02Out
out : OutUE0ToBS1 ...
...
Link  :  X2-10In  X2-10In@BS0
...
Link  :  InBS1ToUE0  InBS1ToUE0@UE0
...
Link  :  OutUE0ToBS0@UE0  InUE0ToBS0@BS0
Link  :  OutBS0ToUE0@BS0  InBs0ToUE0@UE0
...
Link  :  X2-01Out@BS0  X2-01Out
...

[BS0]
components : BSprocessor0@BSprocessor BSQueue0@BSQueue
in  :  X2-10In  X2-20In ...
in  :  InUE0ToBS0 ...
...
out  :  X2-01Out  X2-02Out ...
Out  :  OutBS0ToUE0 ...
...
Link  :  X2-10In  X2-10In@BSQueue
Link  :  X2-20In  X2-20In@BSQueue
...
Link  :  InUE0ToBS0  InUE0ToBS0@BSQueue
...
Link  :  Req@BSprocessor  Req@BSQueue
Link  :  Out@BSQueue  In@BSprocessor
...
Link  :  X2-01Out@BSprocessor  X2-01Out
Link  :  X2-02Out@BSprocessor  X2-02Out
...
Link  :  OutBS0ToUE0@BSprocessor  OutBS0ToUE0
...

[UE0]
components  :  processor0@processor  Queue0@Queue
in  :  InBS0toUE0  InBS1toUE0  ...
Out  :  OutUE0toBS0  OutUE0toBS1  ...

Link  :  InBS0toUE0  InBS0toUE0@UEQueue
Link  :  InBS1toUE0  InBS1toUE0@UEQueue
...
Link  :  Out@UEQueue  In@UEprocessor
Link  :  Req@UEprocessor  Req@UEQueue
...
Link  :  OutUE0toBS0@UEprocessor  OutUE0toBS0
Link  :  OutUE0toBS1@UEprocessor  OutUE0toBS1
...
```

3.3. Message Structure

Message structure in this model consists of 6 digits. Four types of messages have been considered for this model. Messages types are UE to UE, UE to BS, BS to UE, BS to BS.

UE to UE messages are about data and ACK exchange between UEs. Figure 11 shows the fields of this message type. The samples in this figure reveals that UE1 wants to send the data packet number 589 for UE2 and in response when UE2 receives such packet it will send the ACK pack for packet sender to confirm packet reception.

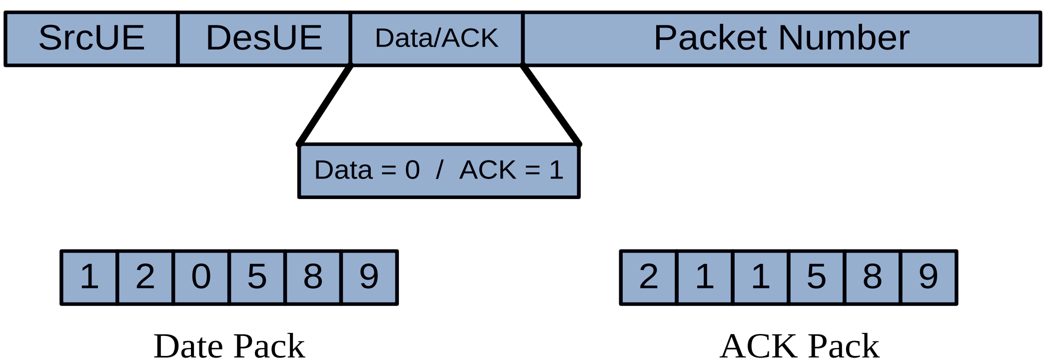

Figure 11: UE to UE message type

BS to UE message type is distinguished from other message types by having 2 in the third digit from left. It can carry information from BS to its UEs. Figure 12 demonstrates the structure of these kind of messages.

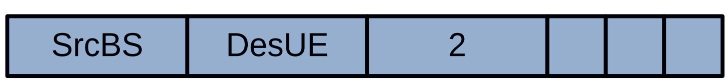

Figure 12: BS to UE message type

UE to BS messages are used when a UE wants to send information about is status to serving BS. This type of messages can be about UE operation mode or UE movement. As it can be seen in Figure 13 if UE0 wants to announce its current mode to its serving BS (which is BS0 in this sample) it will send a message like the ones in this figure. Also if a UE wants to move from current cell to another cell and in hence changing its serving BS it would send a message for current serving BS and announce the future serving BS (Figure 13). By receiving such messages from their UEs, BSs will take suitable act in respond to this message. For example maybe they change their routing tables or send new information for neighboring BSs or for the other BSs in coordination set to notify new status of that UE.

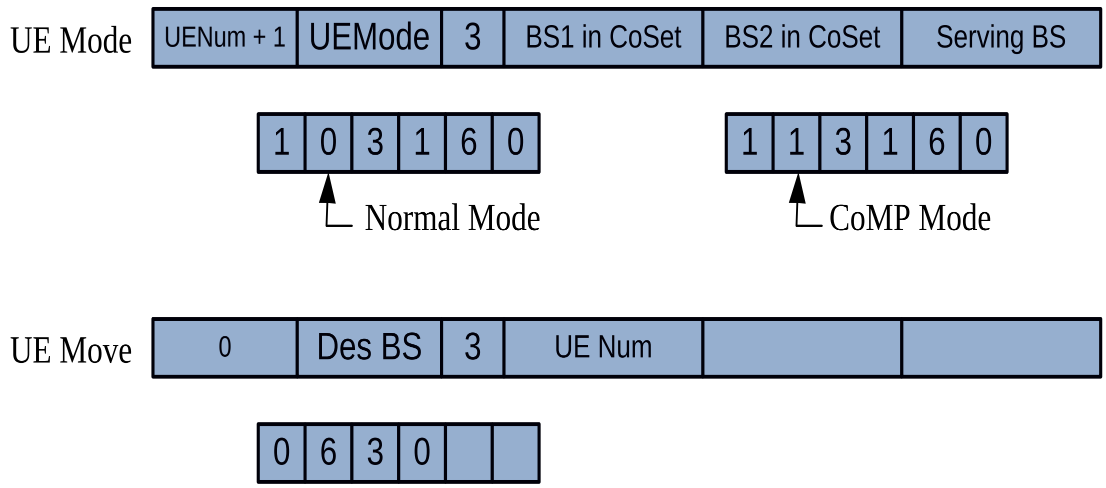

Figure 13: UE to BS message type

The last types of messages are messages which BSs send for each other. As it was said in previous section, BSs use these messages to update each other about network status. For example if BS0 wants to tell the other neighboring BSs that UE0 wants to move from its current cell and its future serving BS is BS6, it will send a message as same as the one in top of the Figure 14. The first three digits from left side of this kind of messages are fixed.

If we consider a scenario in which a UE wants to work in CoMP mode and in particular the network using Coordinating Multipoint approach to provide service for this UE then the serving BS of this UE should send messages for other BSs in coordination set to notify them to decrease the interference level with that UE. The middle message in Figure 14 illustrates that BS0 send a message for BS6 about UE0. The first three digits from left side of this kind of messages are fixed.

Also if a BS wants to send message about its UE operation mode it uses the bottom message structure in Figure 14. In two of those samples serving BS send messages for BS6 and BS1 to say that the UE0 is working in Normal mode and in the other two samples it wants to notify them that the UE0 is working in CoMP mode.

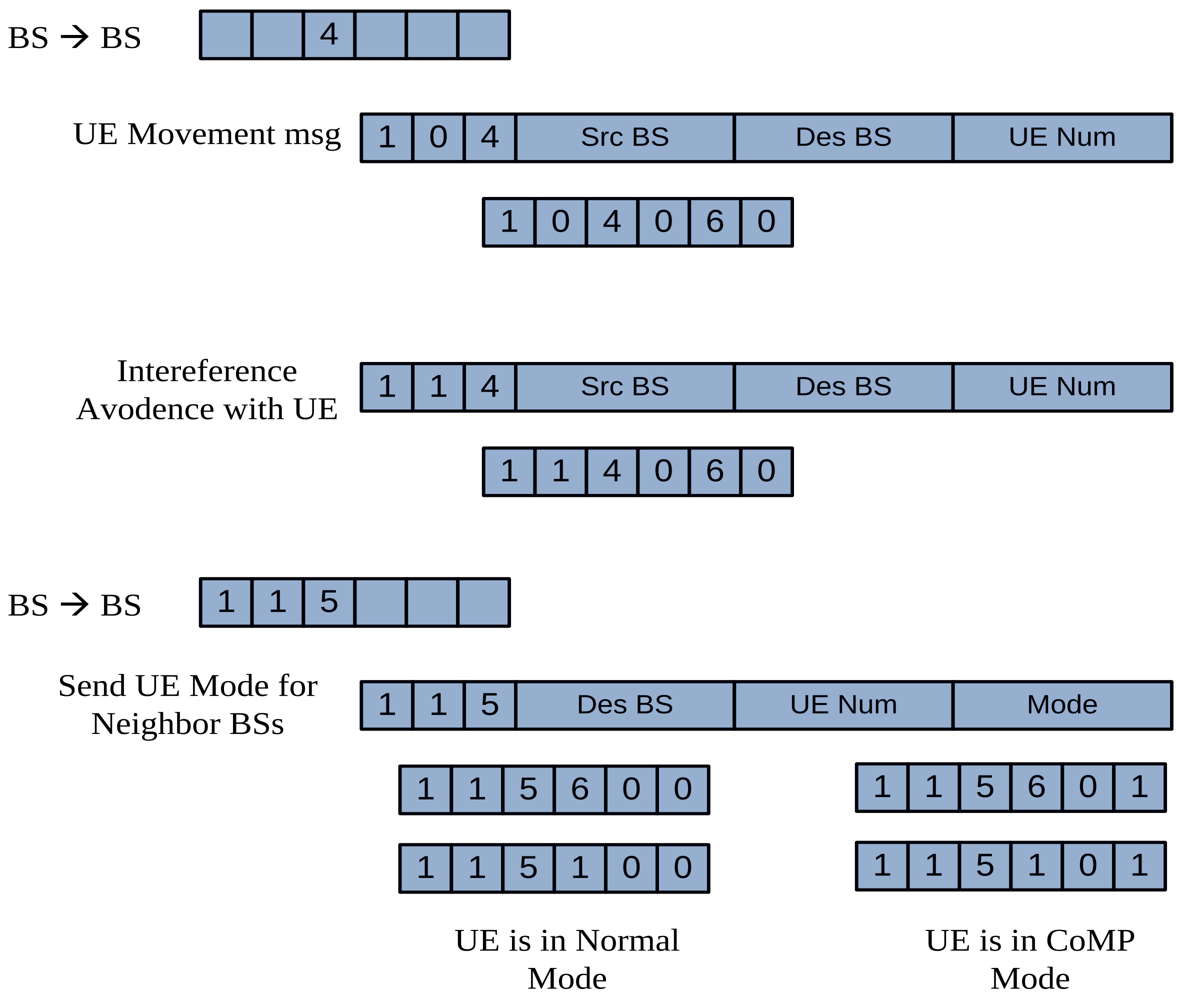

Figure 14: BS to BS message type

4. Simulation Results

As mentioned before each atomic and coupled component has been tested separately with different simulation scenarios which were injected to the network through event file. The final model which is an area with a set of cells, BSs and UEs has been tested under variety random simulation scenarios. In this case UEs randomly generate packets as source for a desired destination and they send these packets through network. Also if a UE is in cell edge zone it can announce its availability for working in CoMP mode to its serving BS. According to network situation serving BS can create a coordination set for that UE to improve its performance.

Also as it was discussed in previous section there is predefined messaging structure for these simulations. Receiver can make decisions according to the structure of received messages. For example in joint processing simulations a UE 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 those BSs identification number too and it has been shown in following:

```
//Time      Port value
…
00:00:00:132 0 103160
00:00:00:170 0 113160
…
```

After receiving such message from a UE, the serving BS create interference message for other BSs which their signal can be sensed by that UR to set the coordination set.

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

From now on the serving BS should send that UE data packets for other BSs in coordination set and then they will send that packet simultaneously for the UE. This approach will increase signal strength at UE side and decreases noises which can reduce signal quality.

```
//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
…
```

In case of coordinated scheduling same events happen and UE send control message for serving BS. After processing the received message in serving BS it will create a coordination set with other BSs which UE senses their signal strong enough. Then the serving BS will send interference cancellation message for other BSs in coordination set. With these scheduling until a UE remain in common area which covered by BSs of coordination set, it can benefits from high data rate and reduced interference.

```
//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
…
```

Followings output samples reveals that how ACK process occurred between UE1 as traffic generator and UE2 as receiver. At first, UE1 started to send data packets for UE2. The following lines are outputs of UE1 processor.

```
00:00:00:020 2 120001
00:00:00:058 2 120002
00:00:00:094 2 120003
00:00:00:130 2 120004
00:00:00:166 2 120005
…
```

These packets were sent to serving BS of UE1 which was BS2 on that moment. BS2 sent these packets for BS server of destination UE. On that time UE2 was in Cell4 and in result BS4 was the serving BS of UE2. Therefore these packets were sent for BS4. The output of BS2 processor shows same thing.

```
00:00:00:022 3 120001
00:00:00:060 3 120002
00:00:00:096 3 120003
00:00:00:132 3 120004
00:00:00:168 3 120005
…
```

By receiving these packets BS4 forwarded them for UE2. The following lines show this communication.

```
00:00:00:026 9 120001
00:00:00:064 9 120002
00:00:00:100 9 120003
00:00:00:136 9 120004
00:00:00:172 9 120005…
…
```

When UE2 received these packets it had to send ACK for each packet to the source of communication which was UE1. UE2 sent ACK packets for its serving BS which was BS4 on that time. The input packets to BS4 show that it received these packets.

```
00:00:00:030 211001
00:00:00:066 211002
00:00:00:102 211003
00:00:00:138 211004
00:00:00:174 211005
…
```

BS4 processed the arrived packets and then forwarded them for serving BS of UE1. BS2 received these packets in the followings time.

```
00:00:00:034 211001
00:00:00:070 211002
00:00:00:106 211003
00:00:00:142 211004
00:00:00:178 211005
…
```

Finally UE1 received the acknowledgments for sent packets.

```
00:00:00:036 211001
00:00:00:072 211002
00:00:00:108 211003
00:00:00:144 211004
00:00:00:180 211005
…
```

As it was mentioned there are test bench for each atomic and coupled models in the attached files (Coordinated Schaduling.zip and Joint Processing.zip) to this report. Each of those components has a special event file (ComponentName.ev: UE1.ev, Cell3.ev and etc) which tries to check the correctness of its component. For each component this event file and its related outputs are in the folder with same name as the component. For example the related files for BS2 are in: …/ Coordinated Schaduling/BS2 and Joint Processing/BS2.

5. Conclusion

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

There are numbers of challenges needed to be responded in term of CoMP and need to be more investigated. These items such as signaling overhead due to setting coordination set can restrict the CoMP usage in mobile networks. Also more study should be done on backhaul delay, overhead and channel status estimation.

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