MODELING AND SIMULATION OF USER MOBILITY AND HANDOVER IN LTE AND BEYOND MOBILE NETWORKS USING DEVS FORMALISM

Baha Uddin Kazi
Gabriel Wainer
Victor Guimaraes da Silva
Department of Systems and Computer Engineering
Carleton University, Ottawa, ON, Canada
{bahauddinkazi, gwainer}@sce.carleton.ca, victorguimaraesdasil@cmail.carleton.ca

ABSTRACT

User mobility and handover are two important functions in mobile networks that provide seamless connectivity of user when moving from one cell to another cell. Hence, handover and its performance are of high importance to improve the performance of mobile networks. In this study, we present a technical overview of mobility and handover management of 3GPP Long Term Evolution (LTE) and beyond mobile networks. We present an open source simulation model of user mobility and handover that allows investigating the performance of handover process within 3GPP LTE and beyond mobile networks. To model the user mobility and handover process we introduce Discrete EVent System Specification (DEVS) formalism, a flexible formal modeling and simulation methodology. We perform modeling and simulation of typical urban area propagation, with different user speed, cell radius and traffic load per cell for both homogeneous and heterogeneous mobile networks.

Keywords: LTE-Advanced, 5G, Handover, Heterogeneous networks, Time-to-Trigger, DEVS, CD++.

1 INTRODUCTION

The new generation of mobile equipment and services increase the number of mobile subscribers and data traffic very fast. The number of mobile broadband subscriptions is growing globally by around 25% each year, and it is predicted to reach 7.7 billion by 2021 (Ericsson, 2016). The network's monthly data traffic is expected to reach 30.6 Exabyte by 2020 (Cisco, 2016). Moreover, 5G networks are expected to provide approximately a system capacity 1000 times higher, 10 times the data rates, 25 times the average cell throughput and 5 times reduced latency when compared to the 4G networks (Wang, et al., 2014; Alsharif & Nordin, 2016; Hossain, Rasti, Tabassum, & Abdelnasser, 2014). Therefore, to overcome the existing challenges it is essential to improve the capacity performance of mobile networks.

The 3rd Generation Partnership Project (3GPP) targets to improve the performance of mobile networks that demand high data rate, more user coverage and seamless mobility. Network densification with the use of small cells is considered one of the effective methods to improve the user coverage of mobile networks. In this approach, big cells are split into small cells to increase spectrum reuse because of limited spectrum. As the size of cells decreases, the number of cells will increase, providing service to more users. However, there are two issues arising when the cell size is reduced: mobility and interference. Therefore, User Equipment (UE) in the cell edge experience frequent handover (HO), and handover failure (HOF). The 3GPP telecommunications standardization body, showed that the increase in the number of handover in small cell network, compared to macro only networks, is 120%-140% depending on the UE speed. Consequently, mobility management became one of the technical challenges to realize the potential coverage and capacity benefits with small cells.

SpringSim-CNS 2017, April 23-26, Virginia Beach, VA, USA

The handover process is used to support the seamless mobility of the UEs. Through the HO process, UEs in active mode can be transferred from the serving cell to the neighboring cell with strongest received power as shown in figure 1.

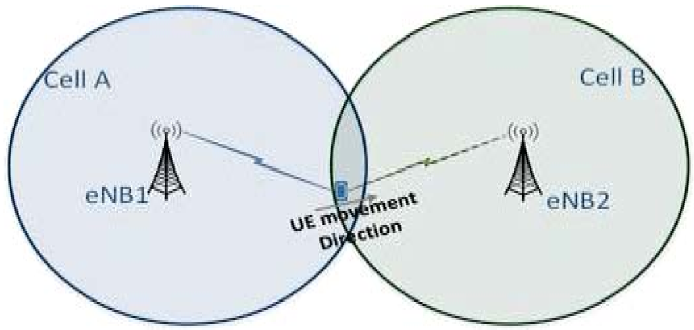

Figure 1: High-level Handover Architecture.

In conventional homogeneous mobile networks, typically same the set of handover parameters are used throughout the networks. However, in heterogeneous networks (HetNets) there is a possibility to degrade the mobility performance if same set of parameters are used for all cells and UEs (Lopez-Perez, Güvenc, & Chu., 2012). Unwanted handovers should be avoided since they will increase the control overhead and the switching load of the network. Moreover, reducing the HOF rate is also important to improve the user experience. Therefore, it is very important to investigate the handover parameters in details to maintain a low HOF rate and number of handover that eventually will increase the performance of the networks.

In this study, we focus on the technical review of handover procedure discussed in 3GPP standardization process of LTE and LTE-A mobile networks. We present an open source simulation model of user mobility and handover that allows us to investigate the performance of handover process within 3GPP LTE and beyond mobile networks. We use Discrete EVent system Specification (DEVS) theory (Zeigler, Praehofer, & Kim, 2000), a flexible formal modeling and simulation methodology, and the CD++ toolkit (Wainer, 2009) and we show how to use this method to model and simulate the LTE-A handover process. We modeled different scenarios for both homogeneous and heterogeneous networks (HetNets) under urban area setting. Moreover, we investigate the HO performance of LTE and LTE-A mobile networks as well as the impacts of various handover parameters such as event offset, time-to-trigger (TTT) and UE speed.

The rest of the paper is organized as follows. We discussed background and related works in section 2. In section 3, we briefly provide an overview of the handover process discussed in the standardization process of LTE and LTE-A mobile networks. The simulation models built using the DEVS formalism is presented in section 4. In section 5, we show different simulation results that summarize the performance of the HO process for both homogeneous and heterogeneous networks. Finally, in section 6 we concluded the paper with future works.

2 BACKGROUND AND RELATED WORKS

3GPP LTE and LTE-Advanced technologies target to fulfill the demand of mobile networks by improving data rates, cell capacity, seamless mobility, etc. To do so, 3GPP adopted a number of technologies including Multiple Input Multiple Output (MIMO), carrier aggregation, mm-wave communication, Coordinated Multi-Point (CoMP) and Heterogeneous Networks (HetNets) in LTE and beyond cellular networks (Jungnickel, et al., 2014; 3GPP, 2016; Alsharif & Nordin, 2016).

Among the various techniques, it has been shown that heterogeneous networks can provide services to massive number of users (Wang, et al., 2014; Sun, Gao, Peng, Wang, & Song, 2013; Jungnickel, et al., 2014). Heterogeneous cellular Networks (HetNets) are comprised of different types of small cells with different capabilities. These include Pico eNB (PeNB), Femto or Home eNB (HeNB) and Remote Radio

Head (RRH). RRHs are mounted outside the macro base station and are connected to the Base Stations (BS) via optical fiber. RRHs do not have baseband units, and the central macro BS is in charge of control and baseband signal processing. Pico eNBs are operator installed low power nodes with the same backhaul and access features as macro BS. The typical transmit power range of a pico eNB is 23 to 30 dBm (Lopez-Perez, et al., 2011). Home eNBs are low power user deployed access points. The typical transmit power of HeNB is less than 23dBm and coverage area is considered less than 50 meters (Lopez-Perez, et al., 2011). These low power small cells can reduce the load of the macro cells and increase the user coverage. However, these small cells can result to increase interference and mobility.

The authors in (Dimou, et al., 20009) investigate the handover failure rate of homogeneous LTE networks. They also show the impact of layer 1 control channel errors on HO performance. Vasudeva et al. in (Vasudeva, Simsek, López-Pérez, & Guvenc, 2015) introduce a new model for analyzing the performance of handover process in HetNets. In (Lopez-Perez, Güvenc, & Chu., 2012), a review of the handover process is discussed, and some technical challenges for mobility management in HetNets are identified. 3GPP (3GPP, 2013; 3GPP, 2015) discuss about the different deployment scenarios and challenges of small cell enhancements (HetNets). In (3GPP, 2016; 3GPP, 2015) 3GPP specifications discussed details of the handover process of mobile networks. In (Ishii, Yoshihisa, & Hideaki, 2012; Jha, Kathiravetpillai, Rath, & Koc., 2014), the authors show how control-plane and data-plane separation (dual connectivity) could be a promising technology to achieve mobility enhancement. In dual connectivity, UE stay connected to macro cell in control plane and received data from both macro and small cell.

There is a variety of simulation platforms for modeling and simulation of LTE and LTE-A networks, including NS3, OPNET Modeler, OMNET++, etc. (Khan, Bilal, & Othman, 2012; Tavanpour, et al., 2015). In (Piro, Baldo, & Miozzo, 2011), the authors presents a module developed for the simulation of the LTE technology in NS-3, which focuses on the aspects related to the channels, physical (PHY) and medium access control (MAC) layers of E-UTRA. SimuLTE (Virdis, Stea, & Nardini, 2014) is a simulator for the data plane of the LTE/LTE-A Radio Access Network and Evolved Packet Core. This simulator is based on OMNeT++ a general-purpose discrete event based simulation framework.

As we mentioned earlier, we used the CD++ platform for M&S, which implements DEVS and Cell-DEVS theory (Wainer, 2009). DEVS provides a number of advantages for modeling and simulation of real world dynamic systems. The hierarchical and modular nature of DEVS allows the description of the multiple levels in protocols, as well as it enhances the reusability of a model. It reduces the computational time by reducing the number of calculation for a given accuracy using discrete-event simulation. The portability and interoperability nature of DEVS allows a model to be extended with different DEVS based simulators. Finally, the use of formal modeling techniques facilitates model verification. In this research, we will not compare different modeling and simulation methodologies, but we are interested in showing the use of DEVS for modeling the mobility and analyzing handover parameters to see how they affect the performance of HO process in both homogeneous and heterogeneous mobile networks.

3 HANDOVER PROCESS IN 3GPP LTE AND LTE-ADVANCE

3GPP specifies the handover procedure for LTE and LTE-Advanced mobile networks that supports user's mobility across the network. In LTE and LTE-advanced mobile networks, UE-assisted network-controlled handovers are performed (3GPP, 2016). In UE-assisted network-controlled handovers, the decision to move from one cell to another cell is made by the serving eNB based on the measurement report (MR) received from the UE. The 3GPP defines the handover process for LTE and LTE-A cellular networks in (3GPP, 2016; 3GPP, 2012).

A HO process completes into five different steps. *1*: The UE measures the downlink signal strength periodically. *2:* The UE processes the measurement results. *3:* The UE sends the measurement report (MR) to the serving eNB based on predefined HO criteria. *4:* The Serving eNB takes the handover decision based on the received MR. *5*: The UE receives a handover command from the serving eNB and it completes the handover. For modeling, handover process of an UE is divided into 3 states (3GPP, 2012):

State 1: Before the handover criteria (event A3) is satisfied.

State 2: After the handover criteria is satisfied but before the handover command is successfully received by the UE from the serving eNB.

State 3: After the HO command is received by the UE from serving eNB, but before the HO process successfully complete. Figure 2 shows the details states of the handover process.

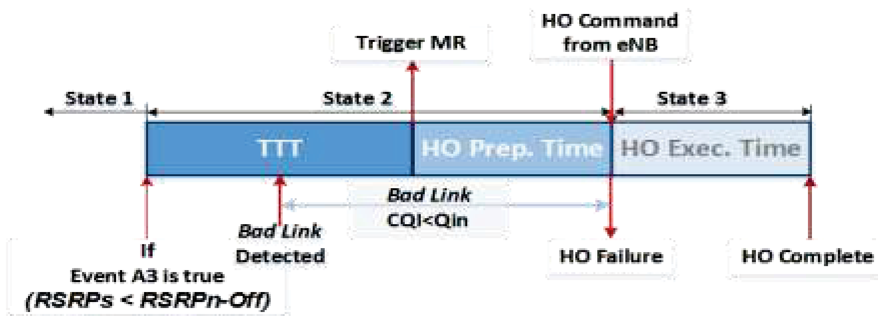

Figure 2: Block Diagram of Handover States.

The UE calculates reference signal received power (RSRP) every 40ms and performs linear average over five successive RSRP samples according to the following formula (3GPP, 2016; Vasudeva, Simsek, López-Pérez, & Guvenc, 2015; Lopez-Perez, Güvenc, & Chu., 2012).

$$M(n) = \frac{1}{5}\sum_{k=0}^{4} RSRP_{l1}\,(5n-k) \tag{1}$$

Where $RSRP_{l1}$ is the RSRP sample measured every 40 ms as stated before, n is the discrete time index of the RSRP sample and k is the delay index of the filter. As a result, handover measurement period for UE in L3 becomes 200ms. Once the L3 filtered RSRP of the serving cell is lower than the target cell minus A3 offset or hysteresis margin, UE starts time to trigger (TTT) timer (Lopez-Perez, Güvenc, & Chu., 2012; Kuang, Jakob, Zarah, Heinz, & Joachim, 2015).

$$\text{Event A3: } RSRP_s < RSRP_n - Off \tag{2}$$

The handover process is performed mainly via the radio resource control (RRC) layer between UE, serving eNB and Target eNB in the control-plane. Figure 3 below shows the message sequence diagram of LTE and LTE-Advance HO process (3GPP, 2016). If the A3 event condition is true throughout the TTT, the UE sends MR to the serving eNB once TTT expires. After receiving the MR from UE, the serving eNB takes the handover decision and issues a handover request message to the target eNB. This handover request carries out admission control procedure for the UE in target cell. After admission control, target eNB sends a handover request Ack message to the serving eNB. When the serving eNB receives the handover request Ack, data forwarding from serving eNB to target eNB starts and the serving eNB sends a handover command (RRC Conn. Reconf) to the UE. UE then synchronizes with the target eNB and sends a handover complete message (RRC Conn. Reconf. Complete) to the target eNB. Therefore, intra eNB handover process of the UE is complete, and the target eNB becomes serving eNB and starts transmitting data to the UE. The new serving eNB sends a path switch request to the serving gateway to inform the core network that it is the new serving eNB for the UE. After that, the serving gateway sends a modify bearer response message to the new serving eNB and switched the downlink data path from previous serving eNB to new serving eNB. Finally, new serving eNB sends message to the old serving eNB to release the resource for the UE.

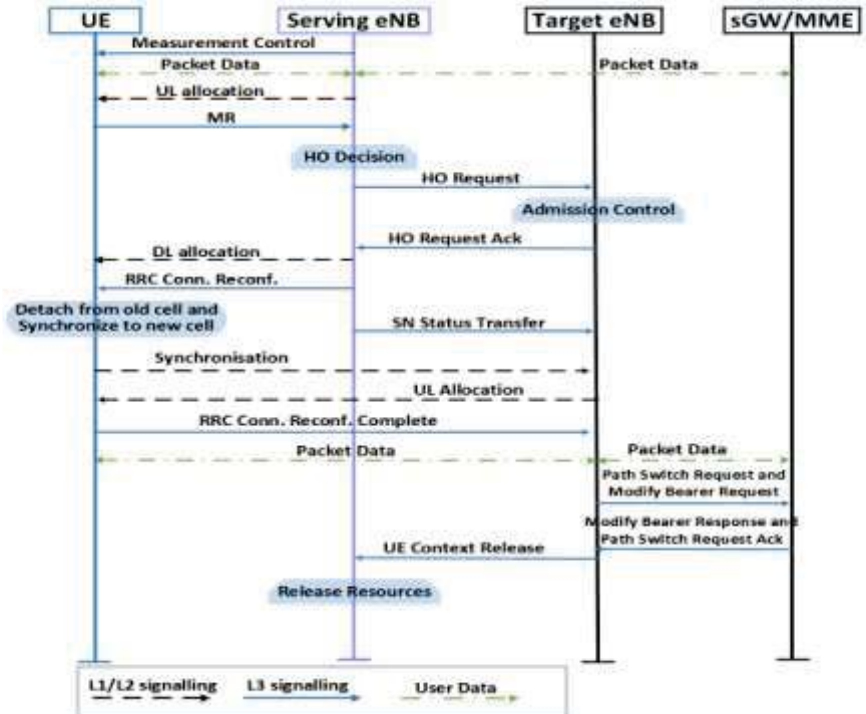

Figure 3: Message sequence for handover process.

4 DEVS MODEL ARCHITECTURE FOR USER MOBILITY AND HANDOVER

4.1 Network Architecture

To study the handover process in LTE and LTE-Advance we consider both homogeneous and heterogeneous networks as suggested in (3GPP, 2013). Figure 4(a) shows the homogeneous network with 19 cells. The Macro eNBs within the cells are connected using X2 link. The numbers of UEs varies in different scenarios and discuss details in simulation and results section. Figure 4(b) shows a heterogeneous network with 19 macro cells and 72 Pico cells. The connection between macro eNBs to macro eNBs and Pico eNBs are X2 links. UEs connect to the macro eNBs and/or Pico eNBs through radio links.

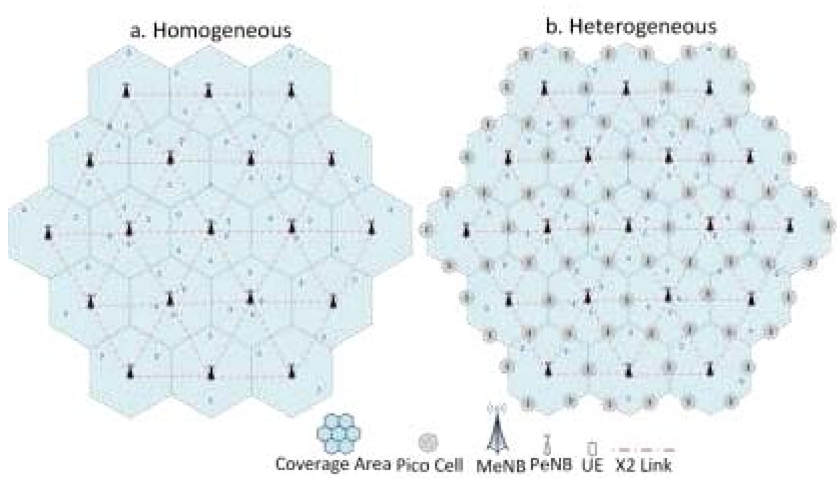

Figure 4: Simplified Network Architectures.

4.2 Model Specification

We developed a DEVS model to analyze the handover process in LTE and beyond mobile networks. The structure of the model is shown in figure 5.

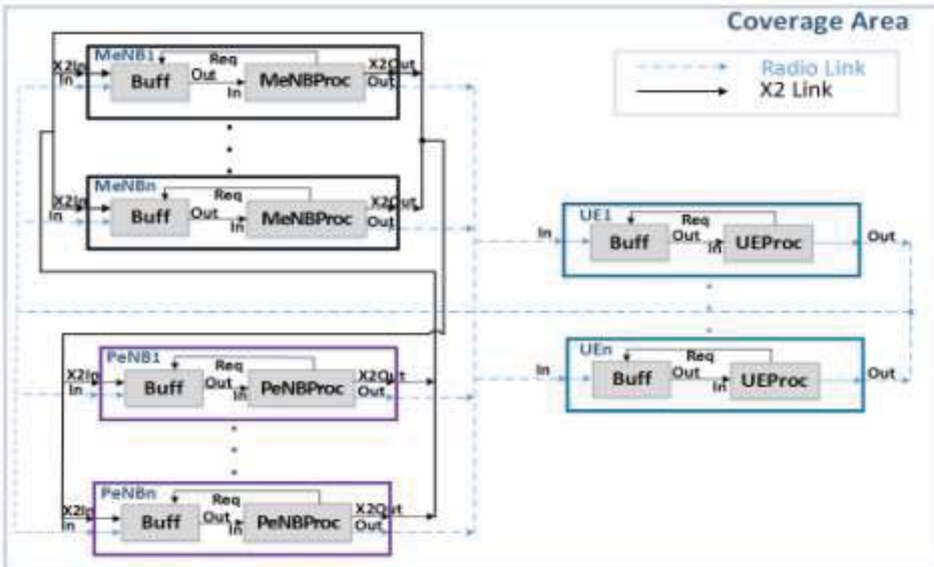

Figure 5: Simplified DEVS model for User Mobility and Handover.

The top level coupled model is the geographic area, which includes a number of cells. Each cell contains one Macro eNB, multiple Pico eNBs and many UEs. Each MeNB, PeNB and UE coupled model is composed of two atomic models named *Buff* and *Proc*. The *UEProc* calculates the RSRP every 40 ms and checks the handover criteria. If it satisfy the HO criteria UE generates the MR and sends to the serving eNB through the output port (Out). The eNB *Buff* acts as a buffer for the eNB. Once the eNB receives a message, the eNB *Buff* pushes it in a queue. The message is popped out from the queue and forwarded to the *MeNBProc* when a request is received from the processor. The *MeNBProc* takes the handover decision and sends handover request to the target eNB through X2Out port. After receiving the handover request ACK from the requested eNB, serving *MeNBProc* sends handover command to UE through the output port (Out). In the above Figure 5, the black solid links connecting the MeNBs and PeNBs represent the X2 links and dashed blue line represents the radio link between the UEs and MeNBs & PeNBs. Moreover, MeNBs, PeNBs and UEs could be any number based on the simulation scenario. This DEVS model is used for analyzing handover process in homogeneous and heterogeneous networks with minimum changes, which is one of the advantages of DEVS.

4.3 Software Structure

The model is implemented in the CD++ toolkit, an open source simulation platform that implements DEVS methodology. Figure 6 below depicts a simplified UML class diagram of the model discussed above. The MeNB class and the PeNB class represent the MeNBProc and the PeNBProc respectively. MeNB and PeNB classes characterizes with id, position, transmit power, frequency etc. The UE class characterizes the UEProc with the properties such as id, position, speed, power, TTT, offset etc. The UE class, atomic component, calculates RSRP periodically based on the formula discussed above and sends the MR to its serving MeNB or PeNB if it satisfies the handover criteria as discussed in section 3.

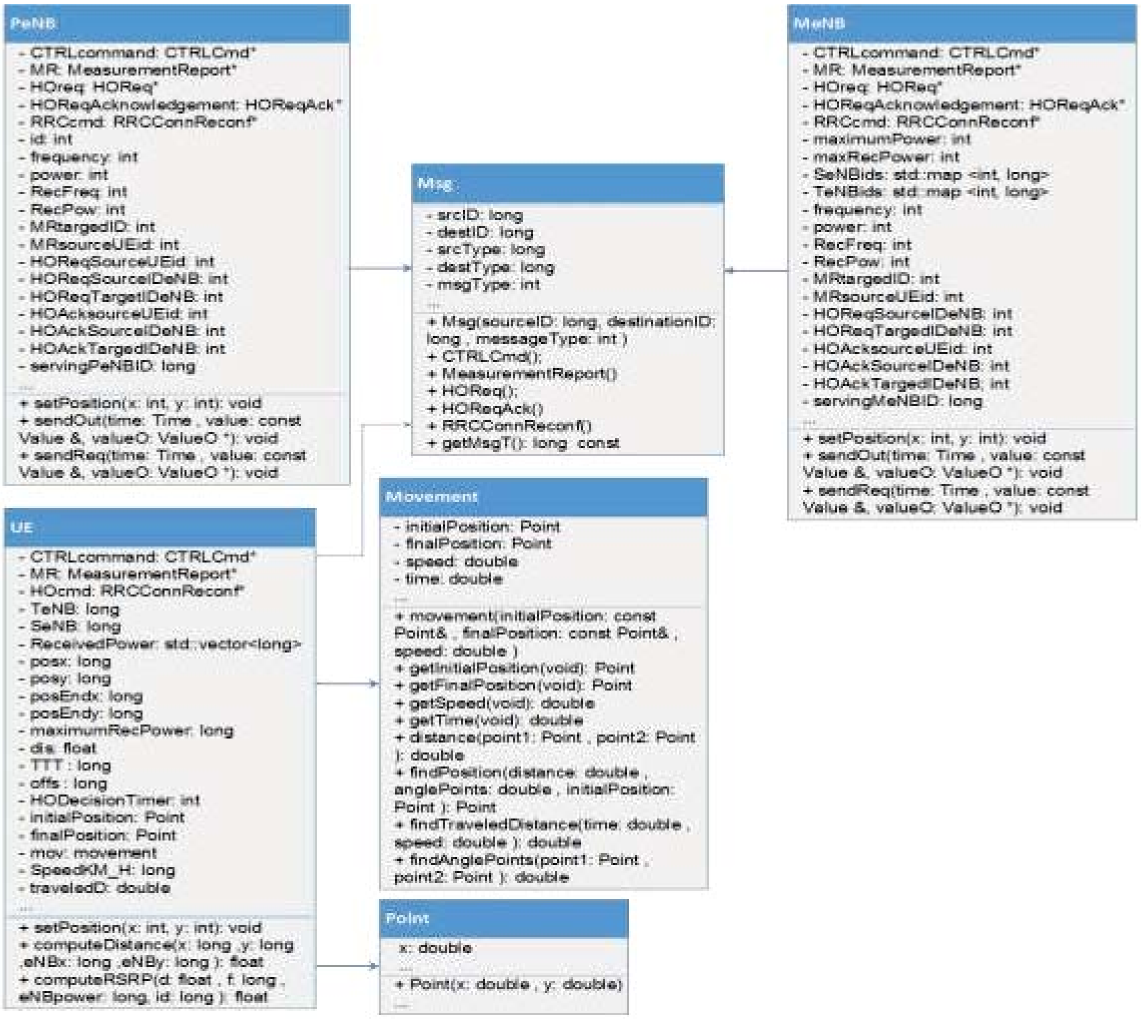

Figure 6: Simplified class diagram of the model.

Figure 4 shows simplified network architecture of the sample simulation scenarios that we have used. We also defined different parameters suggested in 3GPP specifications for LTE and LTE-Advanced mobile networks. Using this information, we ran a series of simulations on this model, using the initial assumptions summarized in table 1, which are based on 3GPP specification suggested in (3GPP, 2016; 3GPP, 2015; 3GPP, 2013).

Table 1: Simulation Assumptions.

Parameters	Values
Number of macro eNBs	19
Number of Pico eNBs	4 per Macro cell and 10 per Macro cell
Number of UEs	50, 100 , 150, 200
UE Distribution	Uniform: randomly into the macro cell area
Frequency	2000 MHz (Macro), 35000MHz (Pico)
Macro eNB Transmit power	43 dBm

Small eNB Transmit Power	30 dBm
Cell Radius	500 m
Antenna gain	12 dBi (Macro eNB), 05 dBi (Pico eNB) and 0 dBi (UEs)
RSRP Sample	Every 40 ms
TTT (ms)	160
A3 offset	3 dB
UE speed (km)	3, 10, 20 ,30
MeNB to PeNB distance	ISD > 100m
PeNB to PeNB distance	ISD > 50m
Handover preparation time	50 ms

In our simulation scenarios, cells are considered in an urban area. The propagation model for macro cell and Pico cell is considered based on the 3GPP standard as follows (3GPP, 2013; 3GPP, 2010):

$$\text{Macro Cell: } 128.1 + 37.6log_{10}(d) \tag{3}$$

$$\text{Pico Cell: } 147 + 36.7log_{10}(d) \tag{4}$$

Where *d* is the distance between UE and BS. The UE calculates the RSRP every 40 ms, and based on the handover criteria (A3 event), it generates MR message and sent this message to the serving eNB. The serving eNB takes the HO decision for the UE based on the received MR.

5 SIMULATION RESULTS

Figure 7 shows a comparison between the handover approaches of homogeneous and heterogeneous networks with respect to the frequency of handover as a function of number of UEs. In this case, we considered 19 macro cells for homogeneous networks and 19 macro cells and 72 Pico cells for HetNets as shown in figure 4. For HetNets, we considered both HetNet scenario 1 and HetNet scenario 2 as suggested by 3GPP in (3GPP, 2013). In HetNet scenario 1, the same carrier frequency (2000 MHz) is used for both macro and pico eNBs, and in HetNet scenario 2, they use different frequencies (2000MHz and 3500MHz), as suggested by (3GPP, 2013). All the UEs are initially connected to the macro eNBs based on the received signal strength. The speed of the UEs is considered 3km/h and the UEs move at random over the coverage area. The simulation time for the four sets (50, 100, 150 and 200) of UEs is the same. As seen in figure 7, heterogeneous networks with same frequency for both macro and Pico increase the handover over 100% compare to homogeneous networks. HetNets with different frequency for macro and Pico reduce the number of handovers over HetNets with same frequency. However, with compare to homogeneous networks the increase of handover is significant.

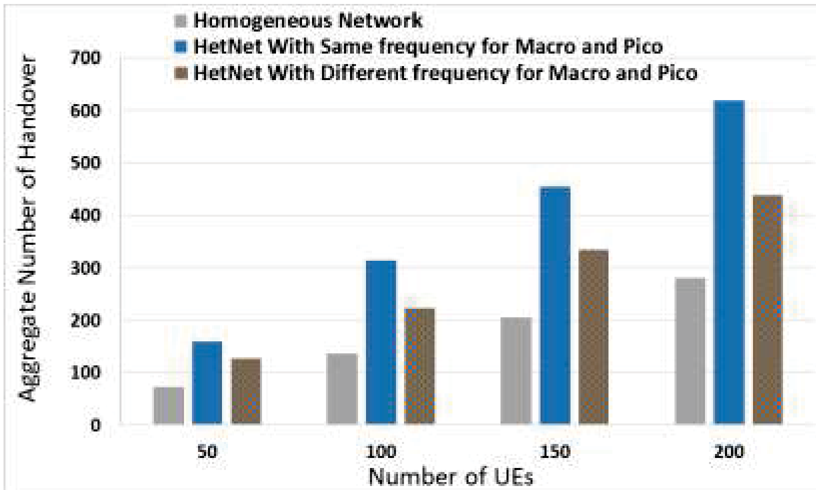

Figure 7: Number of handovers with respect to number of UEs.

Figure 8 shows a comparison between the handover approaches of homogeneous and heterogeneous networks with respect to the number of handovers as a function of UEs speed. In this case, we considered the same network setup as before but the speed of the UEs varies. The speed of the UEs is considered 3km/h, 10km/h, 20km/h and 30km/h, and the UEs move random directions all over the coverage area. The number of handovers has direct relation to the speed of UE. In this simulation results we observed how the handover behaves with the changes of UE speed for both homogeneous and heterogeneous networks. The results clearly show that the increase of UE speed also increase the difference of the number of handovers between homogeneous and heterogeneous networks.

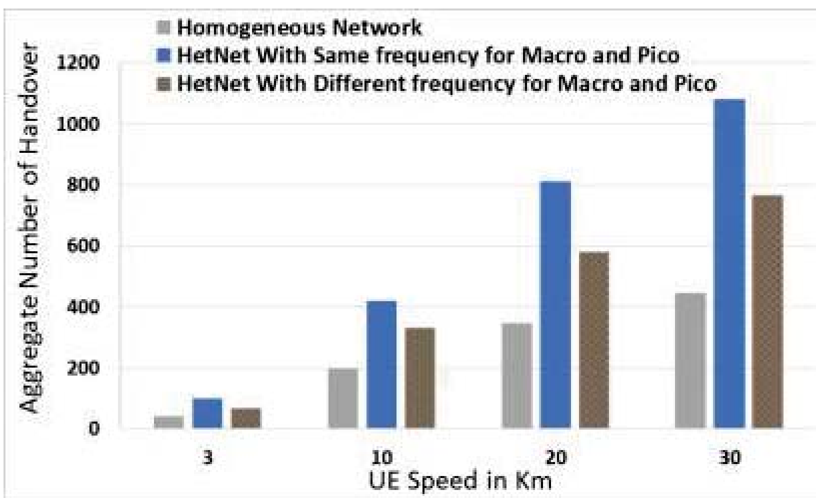

Figure 8: Number of handovers with respect to UE speed.

In figure 9(a), we considered a simulation scenario where each macro cell has about 4 Pico cells. In figure 9(b), we considered a simulation scenario where each macro cell has about 10 Pico cells. We increase the density of HetNets to see how it behaves with respect to handovers. All other parameters remain same for both of the simulation scenarios. If we look at the figure 9, it clearly shoes that scenario (b) increased the total number of handovers. More importantly, the percentage of handovers involved with Pico cells increased significantly.

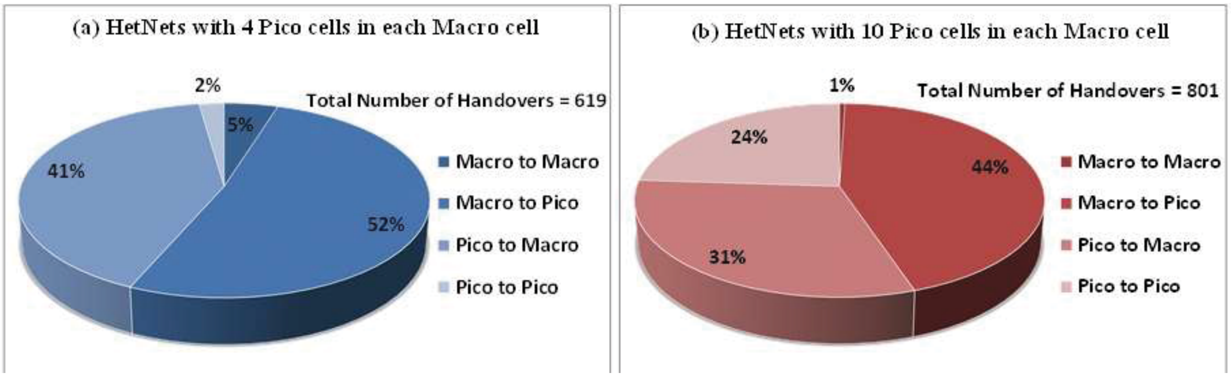

Figure 9: Different types of handovers with respect to the density of HetNets.

According to the simulation results, shown in Figures 7, 8 and 9 we can clearly say that HetNets increase the number of handovers significantly. Moreover, if the density of HetNets increases, the total numbers of handovers increase. More importantly, the handover involved with Pico cells increase significantly. The number of handovers is an important metric for HetNet handover evaluation. The reduction of handover reduces the signaling overhead within the cellular network, which eventually improves the performance of the network. Therefore, designing a new handover procedure for HetNets in future generation mobile networks is a challenge.

6 CONCLUSION AND FUTURE WORK

We presented a technical overview of mobility and handover in LTE-Advanced mobile networks. We also presented a simulation model for user mobility and handover in these using the Discrete Event System (DEVS) Specification. We considered both homogeneous and heterogeneous scenarios for LTE and beyond mobile networks. The CD++ open-source software was used to implement and test the handover model. To investigate the handover process, we used various handover parameters suggested by the 3GPP specifications. Simulation results clearly shows that HetNets increase the number of handovers significantly compare to the homogeneous networks. Moreover, if the density of small cell increases in the HetNets the number of handover is also increase. A potential possibility to expand this work is to examine the handover failure rate for LTE and beyond heterogeneous networks. However, as we mentioned earlier, 5G mobile networks considering the ultra-dense HetNets to improve the performance of cellular networks. Therefore, this study can be further expand to propose a new handover procedure for 5G heterogeneous mobile networks

REFERENCES

3GPP. (2010, 03). *3GPP TS 36.814 V9.0: Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects.* Retrieved July 2016, from http://www.3gpp.org/DynaReport/36-series.htm

3GPP. (2012, 12). *3GPP TR 36.839 V11.1: Evolved Universal Terrestrial Radio Access (E-UTRA); Mobility enhancements in heterogeneous networks.* Retrieved July 2016, from http://www.3gpp.org/DynaReport/36-series.htm

3GPP. (2013, 12). *3GPP TR 36.842 V12.0: Study on Small Cell enhancements for E-UTRA and E-UTRAN; Higher layer aspects.* Retrieved July 2016, from http://www.3gpp.org/DynaReport/36-series.htm

3GPP. (2015, 12). *3GPP TR 36.932 V13.0.0: Scenarios and requirements for small cell enhancements for E-UTRA and E-UTRAN.* Retrieved August 2016, from http://www.3gpp.org/DynaReport/36-series.htm

3GPP. (2015, 12). *3GPP TS 23.009 V13.0.0: 3GPP TS 23.009 V13.0.0.* Retrieved July 2015, from http://www.3gpp.org/DynaReport/spexmtg-NP-23.htm

3GPP. (2016, 06). *3GPP TS 36.133 V14: Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) and repeater ElectroMagnetic Compatibility (EMC).* Retrieved August 2016, from http://www.3gpp.org/DynaReport/36-series.htm

3GPP. (2016, 09). *3GPP TS 36.211 version 14.0: Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation.* Retrieved February 2016, from http://www.3gpp.org/DynaReport/36-series.htm

3GPP. (2016, 09). *3GPP TS 36.300 V14: Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2.* Retrieved October 2016, from http://www.3gpp.org/DynaReport/36-series.htm

Alsharif, M. H., & Nordin, R. (2016). Evolution towards fifth generation (5G) wireless networks: Current trends and challenges in the deployment of millimetre wave, massive MIMO, and small cells. *Telecommunication Systems*, 1-21.

Cisco. (2016). *Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015–2020 White Paper.* Cisco. Retrieved March 26, 2016, from http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html

Dimou, K., Min, W., Yang, Y., Muhammmad, K., Anna, L., Jonas, P., . . . Ylva, T. (20009). Handover within 3GPP LTE: design principles and performance. *IEEE 70th Vehicular Technology Conference Fall (VTC 2009-Fall).* Anchorage, AK, USA.

Ericsson. (2016). *Ericsson Mobility Report.* Retrieved March 26, 2016, from http://www.ericsson.com/res/docs/2015/mobility-report/ericsson-mobility-report-nov-2015.pdf

Hossain, E., Rasti, M., Tabassum, H., & Abdelnasser, A. (2014). Evolution toward 5G multi-tier cellular wireless networks: An interference management perspective. *IEEE Wireless Communications*, 118-127.

Ishii, H., Yoshihisa, K., & Hideaki, T. (2012). A novel architecture for LTE-B: C-plane/U-plane split and phantom cell concept. *Ishii, Hiroyuki, Yoshihisa Kishiyama, and Hideaki Takahashi. "A novel architecture for LTE-B: IEEE Globecom Workshops.*

Jha, S. C., Kathiravetpillai, S., Rath, V., & Koc., A. T. (2014). Dual connectivity in lte small cell networks. *IEEE Globecom Workshops (GC Wkshps).* Austin, Texas, USA.

Jungnickel, V., Manolakis, K., Zirwas, W., Panzner, B., Braun, V., Lossow, M., . . . Svensson, a. T. (2014). The role of small cells, coordinated multipoint, and massive MIMO in 5G. *Communications Magazine, 52*(5), 44-51.

Khan, A. R., Bilal, S. M., & Othman, M. (2012). A performance comparison of open source network simulators for wireless networks. *IEEE International Conference on In Control System, Computing and Engineering (ICCSCE).* Penang.

Kuang, Q., Jakob, B., Zarah, B., Heinz, D., & Joachim, S. (2015). A measurement-based study of handover improvement through range expansion and interference coordination. *Wireless Communications and Mobile Computing, 15*(14), 1784-1798.

Lopez-Perez, D., Güvenc, İ., & Chu., a. X. (2012). Mobility management challenges in 3GPP heterogeneous networks. *Communications Magazine, 50*(12), 70-78.

Lopez-Perez, D., Guvenc, I., Roche, G. d., Kountouris, M., Quek, T. Q., & Zhang, J. (2011). Enhanced intercell interference coordination challenges in heterogeneous networks. *IEEE Wireless Communications, 18*(3), 22-30.

Piro, G., Baldo, N., & Miozzo, M. (2011). An LTE module for the ns-3 network simulator. *Proceedings of the 4th International ICST Conference on Simulation Tools and Techniques.* Brussels, Belgium.

Sun, S., Gao, Q., Peng, Y., Wang, Y., & Song, L. (2013). Interference Management Through CoMP in 3GPP LTE-Advanced Networks. *IEEE Wireless Communications, 20*(1), 59-66.

Tavanpour, M., Mikhail, J., Wainer, G., Moallemi, M., Boudreau, G., & Casselman, R. (2015). DEVS based modeling of shared segmented upload in LTE-A mobile networks. *In Proceedings of the 18th Symposium on Communications & Networking.* San Diego, CA, USA.

Vasudeva, K., Simsek, M., López-Pérez, D., & Guvenc, I. (2015). Analysis of Handover Failures in Heterogeneous Networks with Fading. Vasudeva, Karthik, Meryem Simsek, David López-Pérez, and Ismail Guvenc. "Analysi arXiv preprint arXiv:1507.01586.

Virdis, A., Stea, G., & Nardini, G. (2014). SimuLTE-A modular system-level simulator for LTE/LTE-A networks based on OMNeT++. *International Conference on Simulation and Modeling Methodologies, Technologies and Applications (SIMULTECH).* Vienna, Austria.

Wainer, G. A. (2009). *Discrete Event Modeling and Simulation A Practitioner's approach.* Boca Raton, FL: CRC Press, Taylor & Francis Group.

Wang, C.-X., Haider, F., Gao, X., You, X.-H., Yang, Y., Yuan, D., . . . Hepsaydir, E. (2014). Cellular architecture and key technologies for 5G wireless communication networks. *IEEE Communications Magazine, 52*(2), 122 - 130.

Zeigler, B., Praehofer, H., & Kim, T. (2000). *Theory of modeling and simulation.* San Diego, CA: Academic Press.

AUTHOR BIOGRAPHIES

BAHA UDDIN KAZI is a Ph.D. candidate in the department of Systems and Computer Engineering at Carleton University. He received his MASc in Computer Networks from Ryerson University. He is serving as a member of technical committee of several international conferences. His research interests focus on performance engineering, modeling and simulation, 5G cellular networks and network protocols. His email address is bahauddinkazi@sce.carleton.ca.

GABRIEL A. WAINER, FSCS, SMIEEE, is Professor and Associate Chair for Graduate Studies, Department of Systems and Computer Engineering (Carleton University). He held visiting positions at the University of Arizona; LSIS (CNRS), Université Paul Cézanne, University of Nice, INRIA Sophia-Antipolis, Université Bordeaux (France); UCM, UPC (Spain), and others. He is the author of three books and over 330 research articles; he helped organizing over 100 conferences, being one of the founders of the Symposium on Theory of Modeling and Simulation, SIMUTools and SimAUD. Prof. Wainer is Special Issues Editor of SIMULATION, member of the Editorial Board of IEEE/AIP CISE, Wireless Networks (Elsevier), and others. He received the IBM Eclipse Innovation Award, the First Bernard P. Zeigler DEVS Modeling and Simulation Award, the SCS Outstanding Professional Award (2011), the SCS Distinguished Professional Award (2013), the SCS Distinguished Service Award (2015) and various Best Paper awards. He is a Fellow of SCS. Email: gwainer@sce.carleton.ca

VICTOR GUIMARAES DA SILVA is an undergraduate student at Federal Center for Technological Education (CEFET/RJ), Rio de Janeiro. He was a visiting undergraduate student at Carleton University. His email address is victorguimaraesdasil@cmail.carleton.ca.