

Implementation of Wrap Around Mechanism for System Level Simulation of LTE Cellular Networks in NS3

Rajendra Singh Panwar and Krishna M. Sivalingam

Department of CSE, Indian Institute of Technology Madras, Chennai, India

Email: rajendra@cse.iitm.ac.in, skrishnam@iitm.ac.in, krishna.sivalingam@gmail.com

Abstract—NS3 is a widely used open source dynamic event driven simulator to test new ideas, algorithms and protocols for networks including LTE cellular systems as guided by 3GPP specifications. This paper presents an addition to the LTE module of NS3 by implementing a wrap around mechanism for the standard 19-site cluster. In the wrap around mechanism, the network is extended to include six additional copies of the original hexagonal cluster, such that all cells have symmetric behavior. This will help obtain a more realistic interference environment. The wrap around mechanism is also extended to smaller 3-site and 7-site clusters which can be used for quick verification before simulating larger network. We also implement a wrap around mechanism for UEs, which allows cells in the simulation to have flexible boundary defined by radio conditions rather than fixed simulation boundary. The simulation results show that the wrap around mechanism, as implemented, provides statistically equivalent interference for all cells in the simulation area. This allows use of the entire simulation data providing statistically valid results in much reduced time.

I. INTRODUCTION

Simulations are used to test, validate and optimize algorithms, protocols and procedures used in various wireless networking technologies. These simulations play a major role during development, standardization and implementation process. Network simulations can be carried out at link level which involves simulating a single or a small number of physical links in great detail or at the network/system level in which a large number of links are modelled along with higher layer interactions between the protocol entities. Link level simulations in wireless networks are designed to study radio propagation phenomenon at small temporal scales sometimes even up to a symbol level. All relevant aspects of PHY layer (such as modulation, coding and interleaving) and MAC layer (such as HARQ) are carefully modelled and implemented. Due to time and space complexity of link level simulation, this method is mostly used for the study of a single link between the user equipment (UE) and the base station (BS).

System level simulations study the behaviour of a cellular network as a set of UEs and BSs connected by multiple wireless links. These are suitable for studying network behaviour over a long period of time with respect to network performance characteristics such as QoS, network coverage, capacity, delay, handover and radio resource management (RRM) aspects. Link level and system level simulations operate at different

time scales and are executed independent of each other. The results of link level simulations are incorporated in system level simulations using static interfaces such as Look Up Tables (LUTs).

There are mainly three approaches for system level simulation of cellular networks such as LTE. These include dynamic simulations, semi-dynamic which are snapshot based Monte Carlo simulations and static simulations. In snapshot based Monte Carlo (MC) method [1], a snapshot represents a set of UEs in the network with random position, state and parameters. These simulations typically have less detailed models as compared to the dynamic approach. Also, time-varying effects are not considered when evaluating these independent snapshots with random UE distributions. These simulations are faster than dynamic simulations. However, to obtain statistically reliable results, many snapshots have to be carried out. The simulation run time depends on the number of snapshots and on the number of UEs. The LTE-A Vienna Simulator [2] is a Matlab based open source simulator that has both link level and a system level simulation module. Its system level module is a snapshot based simulator.

On the other hand, NS3 is a dynamic system simulator which has a module to simulate LTE networks [3]. It is used to study network behaviour with reasonably realistic models for most of the components such as power control, mobility, HARQ, RRC procedures, etc. It is designed to simulate the time-variant behavior of the network. It can provide detailed results, but is very time-consuming and therefore mainly used to perform parameter studies to tune the network settings or to test and verify network algorithms. LTE has many transmission parameters that can be tuned and a large number of timers and counters interact with the system to alter its state in many different ways. NS3 allows verification of effects of feedback and time delays which is either absent or statically set in snapshot based simulations. Another major advantage of NS3 is the availability of a flexible and extendable spectrum model which allows one to simulate interoperability between different technologies such as WiFi and LTE.

In this paper, we describe and analyse an extension of the LTE module of NS3 through implementation of the wrap around mechanism based on geometric distance as introduced in [4] [5]. An alternative mechanism for wrap around based on signal strength has recently been proposed in [6]. Here

we have implemented the widely used distance based wrap around mechanism. Results obtained from the implementation are also presented.

II. BACKGROUND

This section presents the relevant background material.

A. PHY Layer Model in NS3

To simulate and measure the effect of interference in wireless communication, we require a model to represent physical layer effects. In a dynamic system level simulator such as NS3, this model is a trade-off between accuracy and computational complexity. If a signal is represented completely in time domain, we also get to know its frequency domain information. However, it is not possible to use complete time domain representation of a signal in dynamic system level simulations due to prohibitive time and space complexity. We now take a brief look at some of the important physical layer models and implementations in NS3 to approximate physical layer effects in wireless communication.

1) *Signal Representation*: Instead of representing time domain amplitude, NS3 uses Spectral Power Density (SPD) values as a representation of the signal. SPD is sufficient for reasonably accurate frequency-selective channel and physical layer models. Ideally, each frequency component of the signal should be mapped to a SPD value. For practical reasons, entire frequency range is divided into smaller frequency sub-bands and each sub-band is represented by a single SPD value. SPD value for a given frequency sub band is considered constant for a pre-defined duration. Thus a given SPD value approximates the signal for a particular frequency-time block. This model permits simultaneous representation of signals with different frequency time resource partitioning as applicable to various wireless technologies/standards.

At implementation level, NS3 encapsulates the frequency selective channel model as described above, in a set of C++ classes collected into spectrum module [7]. Figure 1 describes the relationship between the major abstract entities involved in the spectrum model.

A signal being received or transmitted is represented by an instance of the *SpectrumSignalParameters* class of the spectrum module. All the parameters needed to process the signal are encapsulated in this object. These include a reference to the transmitter object, a reference to the antenna model object used by the transmitter, the frequency bands along with corresponding SPD values and the time duration for which these values are applicable. Frequency band is represented by class *BandInfo* which contains the lower end, central frequency and upper end of the band. Set of all frequency bands which cover the spectrum bandwidth under consideration are encapsulated in the *SpectrumModel* class. The set of SPD values are a member of *SpectrumValue* class which also has a reference to the corresponding *SpectrumModel* object. In a typical scenario, the spectrum model (frequency bands) is fixed and all instances of *SpectrumValue* refer to the same *SpectrumModel* object.

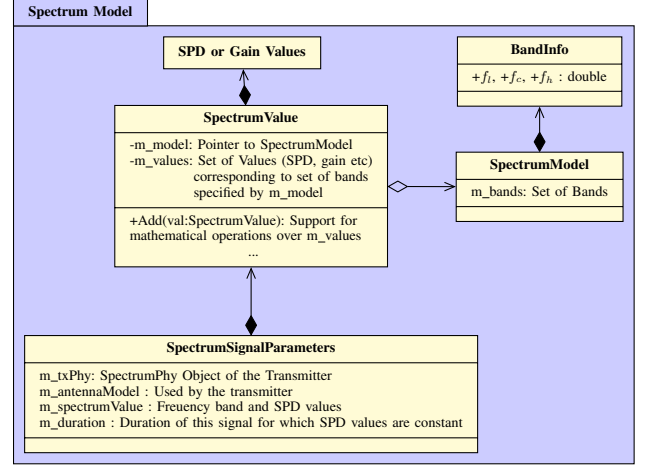


Fig. 1. Class diagram for spectrum model

The number of frequency sub-bands and duration of signal can be varied to suit specific requirement of any given technology whose PHY layer effects are being simulated. For example, to simulate LTE, the frequency sub-band over which the SPD value is constant is 180 kHz. This is equivalent to the frequency spectrum occupied by one resource block (RB). In time domain, signal duration is specified based on whether it is control or data signal. In LTE, control and data channels are separated in time and their durations are pre-defined to a large extent by the frame structure. LTE schedules resources in multiples of RBs and feedback are averaged over several RBs, both in time and frequency domain. Hence, for most system level metrics, flat spectral representation within RB is an adequate model for system simulation of LTE cellular networks.

The spectrum model implementation of NS3 supports interaction among signals by providing arithmetic operations over SPD values of the same sub-band as well as conversion operations for SPD values defined over different sub-bands (i.e. different spectrum model) in the same spectrum range. This allows multiple spectrum models to co-exist and interact in the same spectrum range in a given simulation. This feature is useful to simultaneously simulate different wireless technologies over the same spectrum (e.g. WiFi and LTE).

2) *Simulation of Transmission and Reception of Signals Over the Medium*: The primary components of spectrum module of NS3 responsible for PHY layer transmission and reception are the *SpectrumChannel* and *SpectrumPhy* classes which provide the base classes for channel and receiver/transmitter PHY layer interface respectively. A simulation typically has one (either downlink or uplink) or two (one each for downlink and uplink) *SpectrumChannel* objects. However, each receiver and transmitter is associated with a separate *SpectrumPhy* object. *MultiModelSpectrumChannel* derived from *SpectrumChannel* is used to simulate the channels in LTE simulations. *MultiModelSpectrumChannel* permits use of multiple *SpectrumModel* objects for a given channel as it is equipped with

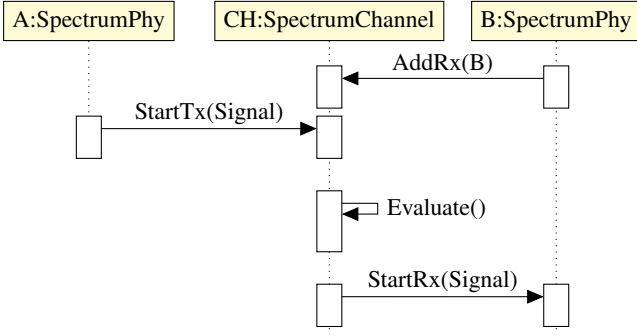


Fig. 2. Transmission and reception of signals

the required conversion function between different spectrum models.

Interaction between *SpectrumChannel* and *SpectrumPhy* objects simulates the transmission and reception of signal over the medium as shown in Figure 2. As part of initialisation, all receivers through their respective *SpectrumPhy* objects register with the *SpectrumChannel* object through its *AddRx(SpectrumPhy)* interface. A transmitter through its *SpectrumPhy* object initiates signal (a *SpectrumSignalParameters* object) transmission by invoking a transmit function *StartTx(signal)* of the channel object.

For each previously registered receiver, the channel object calculates path loss and propagation delay based on the path loss and propagation models linked to the channel. The transmitter location coordinates are available in the *SpectrumSignalParameters* received by the channel object through the *StartTx* interface. The function *Evaluate()* shown in Figure 2 is a stub representing these actions. The channel schedules receive function *StartRx* of all the registered receivers with the evaluated signal parameters for that receiver after a delay corresponding to the propagation delay. Whether the signal is to be treated as interference or desired signal is determined by the *SpectrumPhy* object of the receiver based on association information received from higher layer. We next describe the concept of wrap around mechanism with reference to hexagonal cellular networks.

B. Wrap Around Mechanism

For network simulation and analysis, hexagon is the most used shape to represent a region covered by a cell site. Even though real cell sites do not have such well defined coverage area and symmetrical distribution, hexagonal shape offers comparatively easier analysis and simulation because of its inherent symmetry. In the following discussion, we refer to each hexagon as a site. The term cell is used to represent a LTE cell with distinct ID. In the case of omnidirectional antenna, sites and cells are equivalent while for multi-sectoral antenna case, each sector is a cell. A typical cluster used for network simulations is the 19-site cluster shown in Figure 3a. However, in this cluster, only the central site is symmetrical from all sides. Data collected from the cells of central site is statistically equivalent to data collected

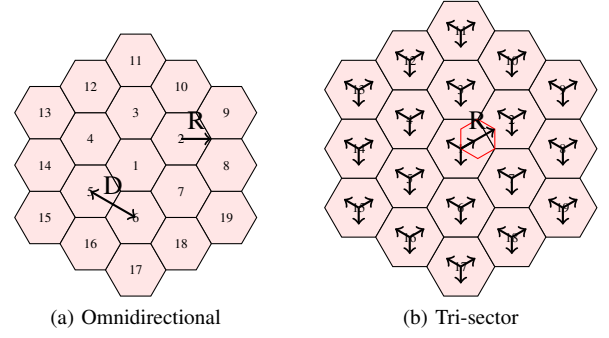


Fig. 3. A hexagonal cluster.

from a network consisting of infinite sites if we ignore the interference beyond two tiers. The data collected from UEs dropped in other 18 sites of the cluster have to be ignored as cells in these sites are statistically not equivalent to cells in an infinite network of sites. All cells of the 18 additional sites and UEs dropped in these cells are fully simulated thus consuming large amount of resource only to provide a statistically uniform interference effect to the cells of central site. Wrap-around enables utilization of data collected from UEs dropped in all the sites. It also affects cell association decision of a UE located at outer tier which now has the option to associate with a cell beyond the boundary with a smaller path loss.

In wrap around mechanism, the network is extended to include six additional copies of the original hexagonal cluster. The original hexagonal cluster is in the center while the other six copies are attached to it symmetrically on six sides, as shown in Figure 4. We refer to the additional clusters as virtual clusters and individual sites/cells within these virtual clusters as virtual sites/cells. There is one-to-one mapping between cells in the central cluster and cells in the displaced virtual cluster. Every virtual cell in the extended region has the same properties as its corresponding cell in the central cluster such as antenna configuration, traffic and fading effects except that they are geographically at different locations. In Figure 4, all sites with site id 6 in the displaced clusters are equivalent to the site id 6 of the central cluster. Theoretical analysis of the hexagonal symmetry in [5] shows that wrap around preserves rotational and translational symmetry on all three axes of hexagonal lattice. In order to be able to perform this mapping, the number of sites in a cluster has to be a rhombic number ρ_{ij} , defined by two positive integer parameters i and j such that $\rho_{ij} = i^2 + j^2 + ij$.

It can be seen from Figure 4 that each of the nineteen sites in the central cluster receives interference from two tiers. For example, consider a UE located in site 9 in central cluster. It receives first tier interference from cells located in sites 10, 2 and 8 in the central cluster and from cells located in sites 17, 13 and 14 from two virtual clusters on the right. Similarly, second tier interferers for UEs in site 9 of central cluster is a combination of cells from sites 19, 7, 1, 3 and 11 in the central cluster and virtual cells from virtual sites 16, 6, 18, 12, 4, 5 and 15 from the two virtual clusters on its right.

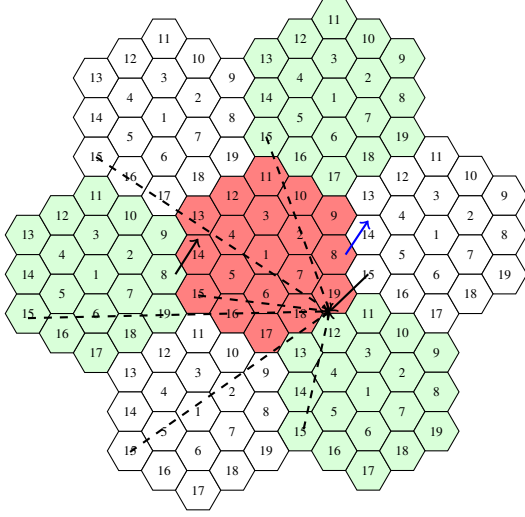


Fig. 4. Wrap around on a 19-cell hexagonal cellular layout.

Sites in the hexagonal cluster may have omni-directional antenna as shown in Figure 3a or sectoral antenna such as tri-sector antenna as shown in Figure 3b where a cell represented by a sector is shown by a small hexagon in red. This means that a 19-site cluster is equivalent to 19 cells in the case of omni-directional antenna and 57 cells in the case of tri-sector antenna.

Implementation of wrap around involves finding the distance between the UE and the nearest version of the cell whose signal is being received. If the coordinate system is defined such that the central site of the central cluster is at (0,0) then the path distance used to compute the path loss and antenna gain of a UE at (x, y) to a base station at (a, b) is the minimum of the seven distances given by Eq. (1). Here, D is the intersite distance and R is the cell radius.

For trisector sites $R = D/\sqrt{3}$ is the sector radius and for omnidirectional antenna $R = D/3$ is the cell radius as shown in Figure 3b and Figure 3a respectively. In Figure 4, when a cell from site 15 of central cluster makes a transmission, a UE in site 19 of the central cluster receives interference from the nearest cell to its right which has the smallest distance calculated based on Eq. (1).

1) *UE Wrap Around*: Another challenge in system level simulation is to identify the boundaries of simulation for data collection and deal with UEs entering and leaving the identified simulation area. Most of the approaches involve defining a fixed boundary for the simulation region and either

$$d = \min \left\{ \begin{array}{l} \sqrt{(x-a)^2 + (y-b)^2}, \\ \sqrt{(x-(a-3R))^2 + (y-(b-4D))^2}, \\ \sqrt{(x-(a+3R))^2 + (y-(b+4D))^2}, \\ \sqrt{(x-(a-4.5R))^2 + (y-(b+3.5D))^2}, \\ \sqrt{(x-(a+4.5R))^2 + (y-(b-3.5D))^2}, \\ \sqrt{(x-(a-7.5R))^2 + (y-(b-0.5D))^2}, \\ \sqrt{(x-(a+7.5R))^2 + (y-(b+0.5D))^2}. \end{array} \right\} \quad (1)$$

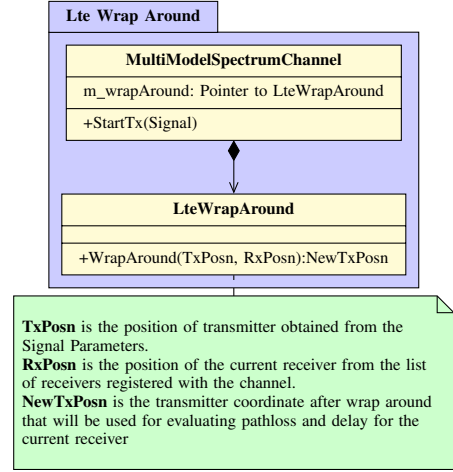


Fig. 5. LteWrapAround

discarding the UEs which move out of the simulation area or artificially let the UEs rebound off the invisible wall into the simulation area.

Such artificial simulation boundaries tend to affect coverage area of cells near the boundary. If UE wraparound is implemented then the cell boundary is realistically determined by the radio environment. Wrap around enables a mechanism which allows UEs to gracefully enter a new region in the simulation area as if there are no edges. Thus there are no lost UEs and no abrupt changes in the movement pattern of UE or radio environment observed by the UE. In Figure 4, a UE movement is depicted by blue arrow from site 8 in the central cluster to the virtual site 14. As soon as UE leaves site 8 it is wrapped around such that it enters site 14 of the central cluster with same speed and orientation as shown by the black arrow.

III. IMPLEMENTATION

This section presents the implementation details of the added wrap around mechanism.

A. Wrap Around for Infinite Grid

As discussed in section II-A, the LTE module in NS3 creates separate instances of *MultiModelSpectrumChannel* class for uplink and downlink. Pathloss components, antenna gain and propagation delay are computed by channel object before invoking receive interface of registered receivers. These computations are based on calculated distance between the transmitter and receiver. We invoke the wrap around mechanism before path loss and delay components are evaluated for a given signal as shown in Figure 6. Since *MultiModelSpectrumChannel* can be used in other cases, the wrap around mechanism is separated from the channel model and is invoked only when LTE is being simulated with wrap around enabled. The wrap around mechanism is encapsulated in a separate class *LteWrapAround* as shown in Figure 5 and deployed as part of LTE module.virtual cell which is closest to the

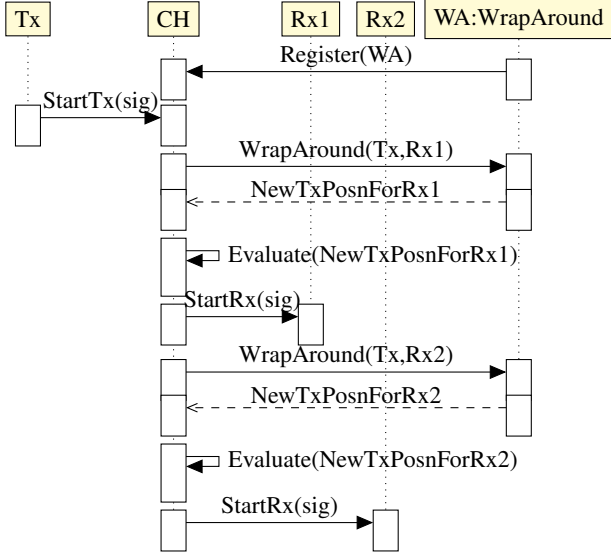


Fig. 6. Invoking Wrap Around Mechanism

UE. The wrap around method evaluates the distance of the receiver from each of the seven replicas of the transmitter and finds the minimum distance as given by Eq 1. Transmitter coordinates corresponding to the minimum distance are used for computation of path loss and delay components. For every single transmission this process is repeated for each receiver registered with the channel.

Sometimes, in order to obtain quick initial results or to demonstrate the feasibility of an idea, it may not be necessary to simulate full two tier interference. For such cases, it is desirable to have the capability to simulate smaller 7-site and 3-site clusters while still using the entire simulation data. We have extended the implementation of wrap around mechanism in NS3 for 7-site and 3-site clusters as shown in Figure 7. The implementation is done with additional functions in *LteWrapAround* class to evaluate corresponding equations derived from the symmetry of 3-site cluster and 7-site cluster layout as given by Eq. (2) and Eq. (3) respectively.

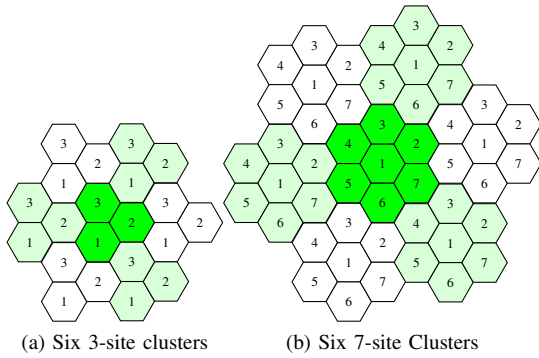


Fig. 7. Wrap around on 3-site and 7-site hexagonal clusters

$$d = \min \left\{ \begin{array}{l} \sqrt{(x-a)^2 + (y-b)^2}, \\ \sqrt{(x-(a-3R))^2 + (y-b)^2}, \\ \sqrt{(x-(a+3R))^2 + (y-b)^2}, \\ \sqrt{(x-(a-1.5R))^2 + (y-(b+1.5D))^2}, \\ \sqrt{(x-(a+1.5R))^2 + (y-(b-1.5D))^2}, \\ \sqrt{(x-(a-1.5R))^2 + (y-(b-1.5D))^2}, \\ \sqrt{(x-(a+1.5R))^2 + (y-(b+1.5D))^2}. \end{array} \right\} \quad (2)$$

$$d = \min \left\{ \begin{array}{l} \sqrt{(x-a)^2 + (y-b)^2}, \\ \sqrt{(x-(a-3R))^2 + (y-(b+2D))^2}, \\ \sqrt{(x-(a+3R))^2 + (y-(b-2D))^2}, \\ \sqrt{(x-(a-1.5R))^2 + (y-(b-2.5D))^2}, \\ \sqrt{(x-(a+1.5R))^2 + (y-(b+2.5D))^2}, \\ \sqrt{(x-(a-4.5R))^2 + (y-(b-0.5D))^2}, \\ \sqrt{(x-(a+4.5R))^2 + (y-(b+0.5D))^2}. \end{array} \right\} \quad (3)$$

B. Wrap Around for UE Mobility

In order to implement this mechanism, there is a need to detect UE movement out of simulation area and to determine the new or wrapped coordinates for the UE. When wrap around is enabled, movement of UE out of simulation area can be detected by the initiation of handover process or new connection to a virtual cell. Thus, to implement UE wrap around mechanism we have to find whether the cell being associated with is a virtual cell and if so what is its location? This information can not be obtained from lower layer elements available in the *SpectrumChannel* during signal transmission and reception. All signals are treated identically by the channel and cell association information is available only at a higher layer in the receiving device.

When a UE selects a cell or a connected UE is handed over to a new cell, it involves a random access procedure. The function to check UE for possible wrap around is invoked only after successful random access to a cell. We exploit the fact that there is no physical object created for the virtual cells. The instantiated objects such as *LteEnbRRC* for a given Cell ID contains the location coordinates of physical cell in the central cluster with given cell ID. The received strength of the signal may be based on the location of a virtual cell with same cell ID. Irrespective of the source, cell ID of the newly associated cell provides access to location coordinates of the physical cell corresponding to the given cell ID. Location coordinates of all six virtual cells corresponding to the same cell ID are obtained using coordinates of the physical cell and hexagonal symmetry. These location coordinates along with current UE location coordinates are used in Eq. 1 to find the virtual or real cell involved in random access.

If the cell being associated with is a virtual cell, UE location is changed to a position inside main cluster by a simple translation maintaining relative orientation between UE and the cell. All other aspects including state information, direction and velocity of UE movement etc remain unchanged thus

TABLE I
SIMULATION PARAMETERS

Network Deployment Parameters	
Macro cellular layout	Hexagonal grid, 7 cell sites 3 sectors per site
Intersite distance(D)	500 m
Minimum BS-UE distance	35 m
Power, Antenna and Channel characteristics	
Antenna Height	30 m(BS), 1.5 m(UE)
Tx Power	46 dBm(BS), 23 dBm(UE)
Carrier Frequency	2.0 GHz
No of Sub Channels	50
Channel Bandwidth	10 MHz

providing same radio environment to the UE as it was before wrap around. Since the random access process is applicable to both new connections and handovers, the wrap around mechanism as implemented also wraps those UEs which get dropped initially in the cluster boundary region. This is a desirable feature as cell boundaries can not be accurately predicted and randomly dropped UEs may initiate initial connection with a virtual cell.

IV. SIMULATION RESULTS

This section presents the simulation results using the wrap around mechanism.

A. Simulation Scenario

We have simulated a tri-sector deployment as shown in Figure 7b with an ISD of 500 m. There are three sectors (each sector is referred to as a cell) per site to which UEs can associate and receive service. We use macro cell scenario corresponding to case 1 of Table A.2.1.1-1 of 3GPP 36.814 [8]. A total of 30 UEs are dropped uniformly in each of the 21 sectors (cells) as per configuration 4b of Table A.2.1.1.2-4 of [8] considering only homogeneous deployment. Other simulation parameters are as summarized in Table I. Antenna model of NS3 was extended to implement tilted 3D antenna pattern as described in [8]. HARQ and error models for data and control as provided in NS3 are enabled. Location of sites is fixed as per hexagonal geometry with center site being at coordinate (0,0).

B. Effect of Wrap Around

1) *Cell Coverage Area*: Figure 8 demonstrates the effect of wrap around on SINR distribution. Unrealistically higher coverage and better SINR can be seen in all three layouts for the cells of outer tier when wrap around is not implemented (left column). When wrap around is implemented (right column) we can see the effect of virtual cells in producing an infinite grid so that effect of interference is statistically equivalent across the simulation area. These SINR maps have been generated by placing a large number of simplified receivers in the entire simulation area in a grid with 10m, 5m and 1m resolution for 19-site, 7-site and 3-site clusters respectively. Since these

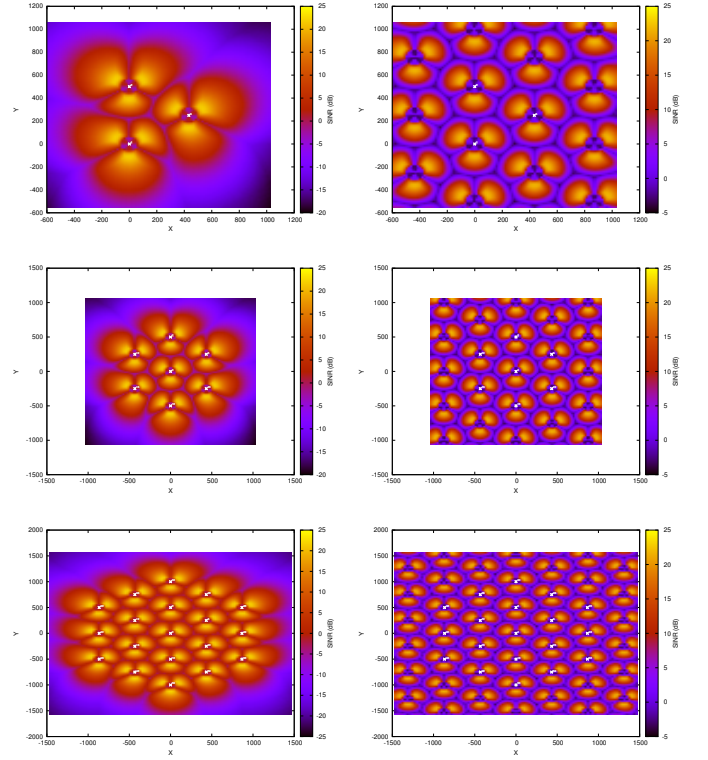


Fig. 8. Effect of wrap around on SINR in clusters with tri-sector hexagonal cellular layout. Each point represents SINR corresponding to the strongest signal. Figures in first column show SINR distribution in absence of wrap around while figures in second column are SINR distribution of corresponding cases after wrap around has been implemented. The left and right images in a given row depict SINR distribution of a particular cellular layout (3-site, 7-site or 19-site clusters) without and with wrap around respectively. For each cellular layout (a row), the SINR color code and the area for which SINR distribution has been mapped is same for both the cases (wrap and no wrap) to enable visual comparison.

simplified receivers are not connected to any particular cell, the strongest signal received is the used to compute the SINR.

2) *System Throughput*: To demonstrate the effect of wrap around on capacity, we simulate the 7-site cluster layout which has one tier interference. Similar to the 19-site cluster, only the center cell has symmetrical interference from all direction. Therefore, 7-site cluster is sufficient to demonstrate the effect of wrap around with much reduced simulation time as compared to 19-site cluster. The cluster is connected to an external server representing the Internet through a 100 Gbps link via a single PGW node and a separate SGW node. Only UDP downlink traffic has been simulated with data rate of 1 Mbps per UE and fixed packet size of 1 KB.

The system was simulated for 32 seconds. The server starts transmission only after a UE has been connected through random access process. Throughput data is reported after 20 seconds of simulation to capture steady state behaviour of the system by avoiding transient effects at initial and final stages of simulation. In both cases (with and without wrap around mechanism), the simulations were repeated with 24

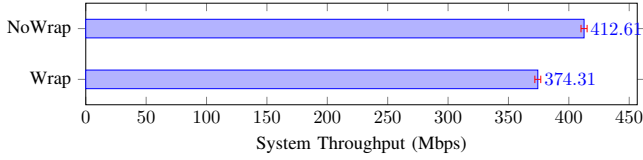


Fig. 9. System Throughput reported with 95% Confidence Interval.

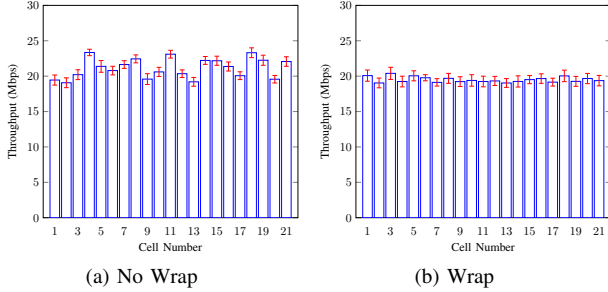


Fig. 10. Per-Cell Throughput reported with 95% Confidence Interval.

different random seeds for uniform distribution of UEs. Effect on total system throughput is shown in Figure 9. In the case of simulation without wrap around we observe statistically significant increase in system throughput as compared to the case when simulation is carried out with wrap around enabled.

3) *Per Cell Throughput*: Per cell throughput statistics is shown in Figure 10. Simulation output without wrap around shown in Figure 10a shows that cells such as 4, 8, 11, 14, 15 and 18 are not statistically equivalent to cells such as 1, 2, 9, 13, 17 and 20. When wrap around is enabled, we observe that all cells are statistically equivalent as shown in Figure 10b.

4) *Empirical CDF of UE throughput and SINR*: The SINR map shown in Figure 8 is the SINR of the strongest signal at all points in the grid irrespective of the source of the strongest signal. We now look at the SINR seen by a connected UE for the signal received from its associated cell. A total of 30 UEs are randomly dropped in each sector. The number of UEs actually connected to the cells varies between 24 to 38 due to the variation in radio environment and UE wrap around. One SINR measurement was carried out per TTI (1 ms) for a duration of two seconds of simulation time. These values were recorded between 16 and 18 seconds of simulation time when all UEs were connected with active traffic source. SINR over each RB was calculated and averaged over entire bandwidth to get one point estimate of wideband SINR. Since full buffer traffic model has not been used, the SINR will also vary due to traffic variations in addition to channel conditions. The 2000 point estimates of wideband SINR per UE obtained during the two second interval were averaged in linear units to arrive at estimate of average SINR received by a UE. These observations were recorded for 24 different random distribution of UEs. The CDF reported in Figure 11 are based on mean of SINR values over multiple runs with pointwise confidence interval evaluated at each data point.

Figure 11a shows that cell 1 which is a sector of the central

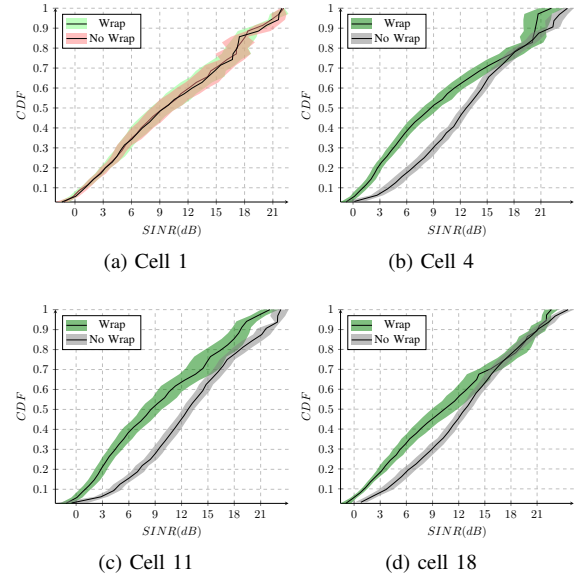


Fig. 11. CDF of UE SINR reported with 95% Confidence Interval.

site is statistically equivalent in both the cases as is evident from symmetry of the cluster. For other cells which are not part of the central cluster we see that the SINR distribution in the simulations without wrap around is optimistic as compared to the case with wrap around enabled.

Cells 1, 2, 3 are sectors of site 1 in the given 7-site central cluster and experience symmetric interference in all directions even without wrap around. Another set of cells correspond to sectors whose main lobe is pointing towards the centre of the cluster and therefore receive partial interference prominently from the sectors of site 1. The group of cells which have antenna orientations towards the boundary of the cluster are the most affected in absence of wrap around. The edge region of these cells is farther away from the cells of site 1. Empirical UE SINR CDFs for all cells in the simulation is shown in Figure 13. The differences in these three groups of cells is expected to be more prominent in standard 19 site clusters because of the presence of an additional tier of interference.

To verify these effects quantitatively we compare the distribution of average UE SINR and throughput in Figure 12. Cell 1 is the control cell since it receives proper interference in both cases as seen by similar SINR distribution in Figure 12a. Without wrap around, UEs connected to cells 4, 11 and 18 receive significantly higher SINR than Cell 1. Table II shows the average SINR values for UEs connected to cells 1, 4, 11 and 18 while the corresponding values for UE throughput is given in table III.

It can be seen that the SINR values are 3 to 4 dB higher when wrap around is not implemented. A corresponding effect is also noticed in the UE throughput. The effect of unrealistically higher SINR will be more prominent for the edge UEs (5 percentile) since these UEs operate in low SINR region. This five to six fold increase in SINR of edge UEs affects coverage area, number of UEs connected and handover

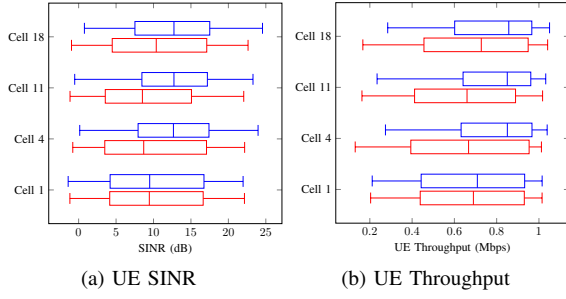


Fig. 12. Boxplot showing the SINR and throughput distribution of UEs. Values represent averages over 24 iterations. There are between 28 to 35 samples (connected UEs) in total for each cell. The box represents the interquartile range (IQR), from the 25th (Q1) to 75th (Q3) percentile and the median is the vertical line inside the box. The lower and upper fence represented by whiskers is $Q1-1.5(IQR)$ and $Q3+1.5(IQR)$ respectively. Wrap around case is plotted in red color and blue color plots indicate data with no wrap around.

characteristics of UEs during simulations.

Figure 14 depicts the CDF of throughput achieved by UEs associated to two typical cells 4 and 18. Throughput of cell 1 from wrap around simulation has been considered as control for comparison. It can be seen that in the wrap around case, throughput CDF of cell 4 and cell 18 are statistically similar to cell 1 and in the no wrap around case it is unrealistically optimistic. Since all cells were subjected to equivalent conditions, the throughput achieved in an infinite grid of cells is expected to be statistically equivalent under similar traffic conditions.

5) *UE Wrap Around*: Figure 15 shows position of some of the UEs before and after UE wrap around. For example, old position of UE labeled O1 was wrapped to the new position labeled N1. At O1, the UE was associated with a virtual cell. At N1, it is associated with a physical cell within the simulation area. It can be seen that the relative position of the

TABLE II
COMPARISON OF AVERAGE UE SINR

SINR (dB)	5 Percentile		Q1		Median	
	No WA	WA	No WA	WA	No WA	WA
Cell 1	0.55	0.25	4.63	4.72	9.92	9.86
Cell 4	3.32	0.60	8.43	4.02	12.95	9.03
Cell 11	3.64	0.52	8.90	3.92	12.98	8.89
Cell 18	2.94	0.55	8.31	4.83	13.04	10.75

TABLE III
COMPARISON OF AVERAGE PER UE THROUGHPUT

Throughput (Mbps)	5 Percentile		Q1		Median	
	No WA	WA	No WA	WA	No WA	WA
Cell 1	0.27	0.25	0.46	0.46	0.73	0.71
Cell 4	0.39	0.26	0.65	0.42	0.86	0.68
Cell 11	0.39	0.26	0.67	0.43	0.86	0.68
Cell 18	0.38	0.27	0.64	0.47	0.88	0.75

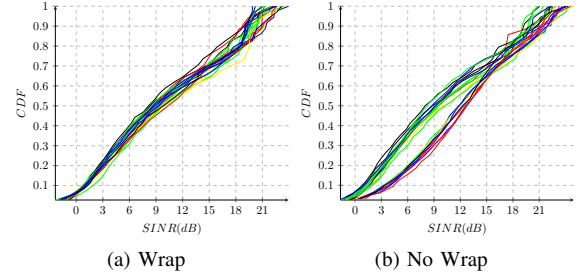


Fig. 13. CDF of UE SINR for all cells.

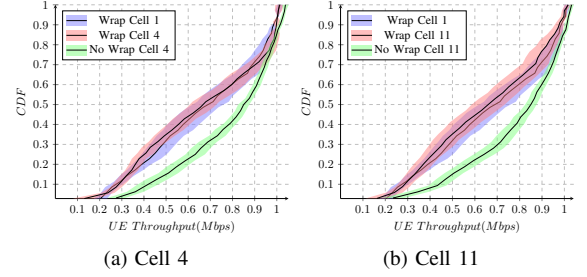


Fig. 14. CDF of UE throughput reported with 95% Confidence Interval.

UE with respect to its connected cell at the new position N1 is similar to what it was at the previous position O1 near the virtual cell. Since we do not make changes to any other aspect including speed and direction of movement therefore the UE does not experience any sudden change due to finite nature of the simulation area.

6) *Heterogeneous Network*: The effect of wrap around mechanism in a heterogeneous two tier network comprising of Macro cells in hexagonal layout and Pico cells deployed randomly within each Macro cell region is shown in Figure 16. In the simulation, Pico cells used omnidirectional antenna with transmit power of 30 dB and two Pico cells were deployed

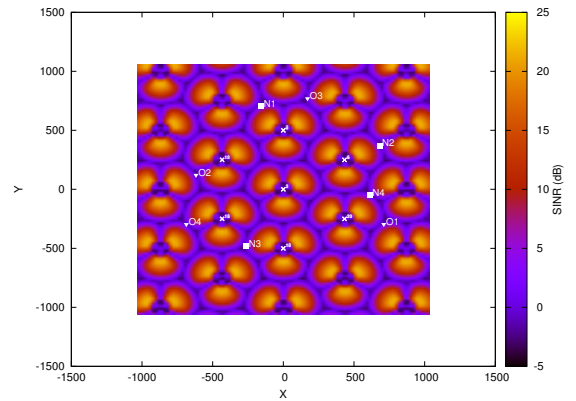


Fig. 15. Effect of UE wrap around in 7-site cluster of tri-sector hexagonal cellular layout. The old position is marked with inverted filled white triangle and labeled as O1, O2 etc. The corresponding position after wrap around is shown with filled white square and labeled as N1, N2 etc.

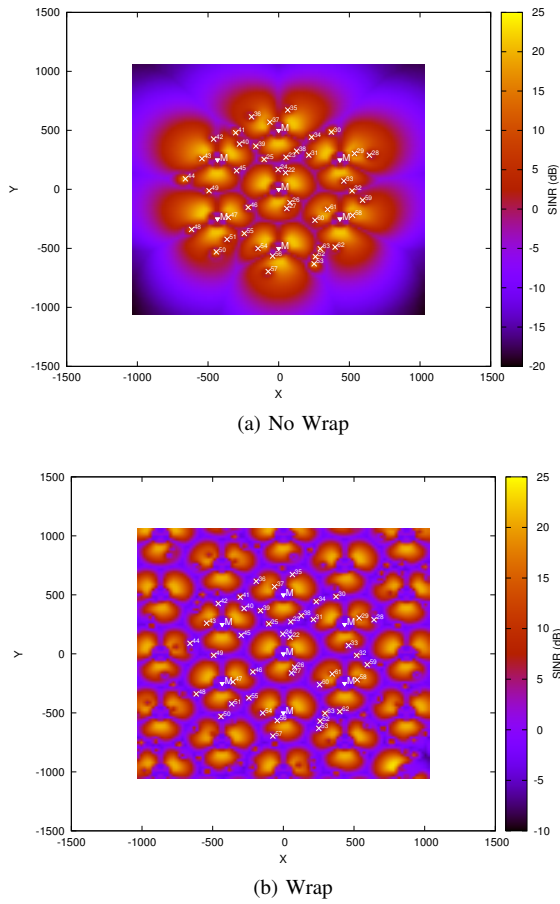


Fig. 16. Effect of wrap around on SINR in Heterogeneous Network with Macro and Pico cells. Macro cells of the central cluster are marked as M.

randomly in each cell of the the 21-cell (7-site) cluster. The Pico cells at the edge receive interference not only from the virtual macro cells outside the cluster boundary but also from virtual Pico cells which are in the vicinity but across the-boundary. The presence of virtual Pico cells can be seen from the distortion of SINR map in the extended region of the the wrap around case in Figure 16b. Therefore, the implementation provides continuity to the heterogeneous environment across cluster boundary. Since NS3 allows multiple technologies to be simulated simultaneously, this can be extended to simulate dynamic system level simulation for interoperability between different radio access technologies (RATs) such as WiFi and LTE. Similar to Pico cells, WiFi access points can be extended to the virtual region using the hexagonal layout of LTE Macro cellular system as the anchor for wrap around mechanism.

7) *Run Time*: These simulations were carried out in a system running Ubuntu 16.04(LTS) 64-bit on a system with an 8-core Intel Core i7-4810MQ CPU 2.80GHz with 16GB RAM. Different runs of the simulation took between 26 hours

to 30 hours of real time in both cases. The increase in run time due to implementation of wrap around varied from 15 minutes to 90 minutes which is negligible compared to the overall run time. It is important to note that for the case of no wrap around, normally data is collected from only one cell thus requiring many repetitions to get similar statistical confidence in per-cell throughput as one single run with wrap around enabled. With wrap around, per-cell throughput data can be averaged over all the simulated cells of the cluster instead of repeating the experiment.

V. CONCLUSIONS

This paper presents the implementation of the wrap around mechanism to simulate effects of boundless network in finite simulation environment for LTE simulations in NS3. This results in considerable savings in simulation resources and the computation time required to get statistically valid results. UE wrap around mechanisms has also been implemented. This allows the simulation area to be dynamically adjusted according to radio conditions rather than using pre-defined boundaries. The extension of wrap around mechanism from standard 19-site cluster to smaller 3-site and 7-site clusters is useful for fast simulation experiments to test new ideas, since 19-site (57 cells in case of trisector antenna) cluster based simulations in NS3 are extremely time consuming. The implementation can also be used for heterogeneous environments and with, some modifications, be extended to multi-RAT networks.

REFERENCES

- [1] M. Turke, "Monte-carlo snapshot analysis for wcdma network performance evaluation," in *Efficient Methods for WCDMA Radio Network Planning and Optimization*. Wiesbaden: Vieweg+Teubner, 2007, pp. 67–106.
- [2] M. Rupp, S. Schwarz, and M. Taranetz, *The Vienna LTE-Advanced Simulators: Up and Downlink, Link and System Level Simulation*, 1st ed. Springer Publishing Company, Incorporated, 2016.
- [3] N. Baldo, M. Miozzo, M. Requena-Esteso, and J. Nin-Guerrero, "An open source product-oriented lte network simulator based on ns-3," in *Proceedings of the 14th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM)*, 2011, pp. 293–298.
- [4] J. Khun-Jush, "CDMA Uplink Power Control Methodology in SEAMCAT (VOICE ONLY)," Qualcomm, Tech. Rep. STG(03)13 r1, Oct 2003.
- [5] M. Iridon and D. W. Matula, "Symmetric cellular network embeddings on a torus," in *Proc. of 7th International Conference on Computer Communications and Networks*, Oct 1998, pp. 732–736.
- [6] A. V. Kini, M. Hosseinian, M. il Lee, and J. Stern-Berkowitz, "Reevaluating cell wraparound techniques for 3d channel model based system-level simulations," in *WCNC*, 2015.
- [7] N. Baldo and M. Miozzo, "Spectrum-aware channel and phy layer modeling for ns3," in *Proceedings of the Fourth International ICST Conference on Performance Evaluation Methodologies and Tools (VALUETOOLS)*, Pisa, Italy, 2009, pp. 2:1–2:8.
- [8] 3GPP, *Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA Physical layer aspects*, ser. TR. 3GPP, 2015, no. TR36.814, Rel-9 v1.3.0. [Online]. Available: <http://www.3gpp.org/ftp/Specs/html-info/36814.htm>