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Modeling Cellular Network Infrastructure in SUMO

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Abstract

Communication networks are becoming an increasingly important part of the mobility system. They allow traffic participants to be connected and to exchange information related to traffic and roads. The information exchange impacts the behavior of traffic participants, such as the selection of travel routes or their mobility dynamics. Considering infrastructure-based networks, the information exchange depends on the availability of the network infrastructure and the quality of the communication links. Specifically in urban areas, today's 4G and 5G networks deploy small cells of high capacity, which do not provide ubiquitous cellular coverage due to their small range, signal blocking, etc. Therefore, the accurate modeling of the network infrastructure and its integration in simulation scenarios in microscopic traffic simulation software is gaining relevance.

Unlike traffic infrastructure, such as traffic lights, the simulation of a cellular network infrastructure is not natively supported in *SUMO*. Instead, the protocols, functions and entities of the communication system with the physical wireless transmission are modeled in a dedicated and specialized network simulator that is coupled with *SUMO*. The disadvantage of this approach is that the simulated *SUMO* entities, typically vehicles, are not aware which portions of the roads are covered by wireless cells and what quality the wireless communication links have.

In this paper, we propose a method for modeling the cellular infrastructure in *SUMO* that introduces a cellular coverage layer to *SUMO*. This layer models cell sites in a reg-ular hexagonal grid, where each site is served by a base station. Following commonly accepted guidelines for the evaluation of cellular communication system, the method fa-cilitates standardized and realistic modeling of the cellular coverage, including cell sites, antenna characteristics, cell association and handover. In order to ease the applicability of the method, we describe the work flow to create cell sites. As a representative case, we have applied the method to *InTAS*, the *SUMO* Ingolstadt traffic scenario and applied real data for the cellular infrastructure. We validate the approach by simulating a *Cellular V2X* system with sidelink connectivity in an urban macro cell environment by coupling *SUMO* enhanced by the proposed connectivity sublayer with *ARTERY-C*, a network simulator for *Cellular V2X*. As a proof-of-concept, we present a signal-to-interference noise ratio (SINR) coverage map and further evaluate the impact of different types of interference. We also demonstrate the effect of advanced features of cellular networks such as inter-cell interference coordination (ICIC) and sidelink communication modes of *Cellular V2X* with dynamic switching between the in-coverage and out-of-coverage mode.

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1 Introduction

Communication networks are becoming an increasingly important part of the mobility system. They allow vehicles, roadside infrastructure and vulnerable road users to be connected and to exchange information. A great number of applications exist, such as online route guidance, safety hazard warnings or traffic light information. While many applications are already intensively used today, they are expected to considerably improve the road traffic efficiency and safety in the future. Also, the communication support future autonomous driving by the exchange of massive amount of sensor data and of messages for maneuver coordination.

The communication impacts the aggregated road traffic flows and the individual behavior of the traffic participants because the reception of the information changes their behavior and interaction, locations, distance and time headways, as well as velocity and acceleration. For example, online route guidance helps drivers to bypass traffic jams. A safety-related hazard warning forces a driver to break, or the reception of the traffic light status may prompt a driver to adapt the speed. For accurate modeling of road traffic, it is therefore indispensable to consider communications.

For a macroscopic representation of aggregated road traffic flows, simplifying assumptions for the communication can be made. For a microscopic model, vehicles and other traffic participants need to be modeled individually along with their specific dynamics. One possible approach is to enhance existing microscopic road traffic models and adapt their parameter settings. However, the communication strongly depends on the capabilities of the communication system and the quality of the communication links. Specifically, today's 4G and 5G networks deploy small cells of high capacity in urban areas, which do not provide ubiquitous coverage due to their short range, signal blocking etc. Also, recent developments in cellular networks facilitate a direct communication among end devices (sidelink) extending the conventional data transmission via the cellular infrastructure (up- & downlink), referred to as *Cellular-V2X*, which is particularly suitable for the exchange of V2X messages [2]. Therefore, the microscopic representation of road traffic requires a detailed modeling of protocols, functions and entities of the communication system with abstraction of the physical transmission. Specifically, we regard the communication infrastructure as integral part of a modern road traffic infrastructure similar to traffic lights.

In the microscopic road traffic simulator *SUMO* [11], the modeling of the communication system and the simulation of the information exchange are not natively supported. Instead, for studying scenarios with realistic mobility and communications, a dedicated, specialized communication network simulator is coupled with *SUMO* via the Traffic Control Interface *TraCI* [17]. The limitation of this approach is that routable *SUMO* entities, typically vehicles, are not aware which portions of the roads are covered by wireless cells and what quality the wireless communication links have.

In this paper, we propose an approach to model the cellular infrastructure in *SUMO*. We describe a generic workflow to create cellular sites (each served by a dedicated base station) containing real world data about the cellular infrastructure. Following ITU-R guidelines [5] for evaluation of wireless communication technologies, the method facilitates standardized and realistic modeling of the cellular coverage, including cell sites, antenna characteristics, cell association and handover. For validation we carry out link level simulations of a *Cellular V2X* system enabled with sidelink connectivity. This is done by coupling *InTAS*, the *SUMO* Ingolstadt traffic scenario, enhanced by the proposed connectivity sublayer with *ARTERY-C*, a network simulator for *Cellular V2X*.

The remainder of the paper is structured as follows: After a review of related work in Section 2, Section 3 provides background on *Cellular V2X*, the network simulator *ARTERY-*

C and modeling of communication aspects. Section 4 describes the modeling of the cellular infrastructure and wireless coverage in *SUMO*. Section 5 presents selected simulation results as proof-of-concept and Sec. 6 concludes the paper.

2 Related Work

Considerable research work has been carried out using *SUMO* in order to develop real world scenarios to simulate vehicular communication. Some of the best scenarios include - Luxembourg *SUMO* traffic *LuST*, *TAPAS* Cologne and Monaco *SUMO* traffic *MOST*, which model all aspects of road traffic, public transport and building structures.[1] Furthermore, the Ingolstadt traffic scenario *InTAS* [10] considers additional parameters such as traffic light conditions and also analyzes real-world data and defines a realistic traffic demand method that fits the dataset. However, the above mentioned scenarios do not model the cellular network infrastructure, which plays a major role in identifying, whether roads or road segments have cellular coverage nor provide information about the link quality. The authors believe that the introduction of the cellular coverage aspect to *InTAS* is a first major step towards developing a real world scenario, where V2X communication is natively enabled in *SUMO*.

Existing simulation frameworks for vehicular applications are capable of supporting complex vehicular traffic models along with online re-configuration and re-routing features. The hybrid simulation frameworks *iTETRIS* [7] and *Veins* [15] couple *SUMO* with the network simulator *ns3* and *OMNeT++*, respectively. Several advanced simulators for V2X communications have been developed on the basis of *ns3* or *OMNeT++*, such as *Artery*, *Artery-C*, *Cellular-VCS*, *OpenCV2X*, *Simu5G* and *SimuLTE* [14, 3, 6, 12, 16, 13]. They can be coupled with *SUMO*, either using *SUMO*'s *TraCI* interface directly or exploiting a simulation framework, such as *Veins*. *Cellular V2X*-specific simulators such as *OpenCV2X* [12] and *Artery-C* [3] are capable of supporting various application scenarios of V2X communication using the above mentioned *SUMO*-based scenarios.

However, in all the above approaches the cellular network infrastructure is modeled inside the communication network simulator (i.e., *OMNeT++* or *NS-3*) and only the vehicle-related information is exchanged between the communication network simulator and *SUMO*. This corresponds to the assumption that vehicles already know that cellular coverage is available. An approach to model various types of cellular environments for e.g. urban macro cell directly inside *SUMO* serves as a step forward towards setting up a close-to-real simulation environment where the vehicle is completely unaware of the availability of cellular network coverage when it enters the simulation.

3 Coupling of a Network Simulator with SUMO

This section presents some of the relevant Cellular V2X concepts such as communication interfaces namely - uplink (UL), downlink (DL) and sidelink (SL), an introduction to the network simulator along with protocol stack description, channel description and a brief overview of types of interferences that we have taken into account.

[1]See https://sumo.dlr.de/docs/Data/Scenarios.html

3.1 Cellular V2X for Backend and Sidelink Communications

V2X communication based on cellular networks enables the continuous exchange of information among vehicles, roadside infrastructure and other road traffic participants. It facilitates the conventional communication between vehicle and network (V2N) to provide backend services and, in addition, realizes direct communication among end devices, i.e., vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P) and vehicle-to-infrastructure (V2I) communication. The direct communication, also referred to as device-to-device (D2D), allows two physically close end devices to use a sidelink without sending the data via the cellular access and core network. Compared to the regular cellular communication via up- and downlink, the sidelink shortens the latency, which is a critical aspect of use cases for vehicle safety and automation [9]. For road traffic efficiency and safety applications, various message types, such as the cooperative awareness message (CAM), the decentralized environmental notification message (DENM), vulnerable road user awareness message (VAM), can be transmitted over Cellular V2X links [1].

3.2 Artery-C for Network Simulation of Cellular V2X

For simulation of the *Cellular V2X* system, we use the network simulator *Artery-C* [3] and couple *SUMO* with it. *Artery-C* models both the control and the user plane of *Cellular V2X* and implements all layers as depicted in Figure 1. The top layer of the protocol stack is for generation and reception of V2X messages. *Artery-C* shares the same upper V2X messaging layer as implemented in *Artery* [14].

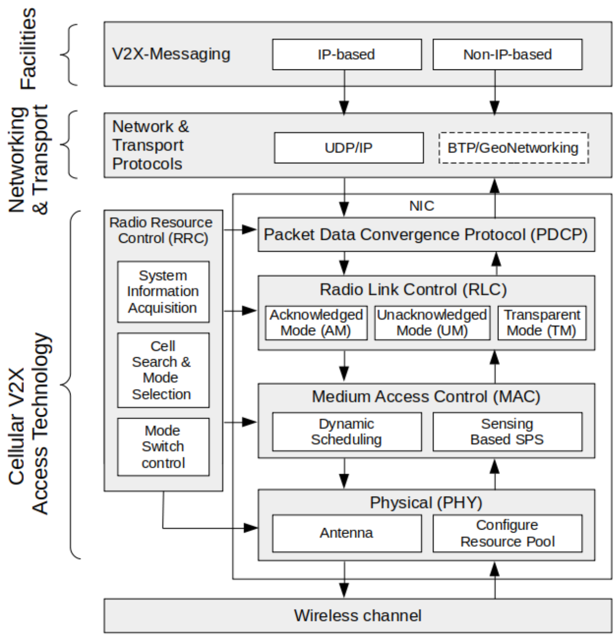


Figure 1: Implementation design of the *Cellular V2X* stack in *Artery-C* [3]

The protocol stack implementation in *Artery-C* is further enhanced by ITU specified stochastic channel models in order to carry out simulations for validation of the cellular network coverage model implemented in *SUMO*. The user plane is directly linked with the *SUMO* traffic model via the `TRaCI` API in order to continuously track the position of the vehicle and identifies whether it is located in the region of cellular coverage or not. The cellular base stations (eNodeB in 4G LTE) and road side units (RSUs) are modelled as stationary modules whereas the vehicles are modelled as dynamic modules. For details of the protocol stack modeling we refer to [3]. The vehicle user equipment (UE) in the simulation have been categorized into two types based on their connectivity to the base station and their geographical location namely (i) in-coverage and (ii) out-of-coverage. This classification of the vehicles directly corresponds to the two operational resource allocation modes in sidelink – in-coverage and out-of-coverage, which are also referred to as mode 3 and 4 in *Cellular V2X* specifications.

In-coverage mode. The vehicles which are inside the cellular coverage region can dynamically connect to the nearby base station which are in turn connected to the enhanced packet core (EPC). From Figure 4 it can be inferred that vehicles in overlapping cell regions have an option to connect to any of the eNodeBs. A vehicle measures the wireless signal strength from all possible eNodeB and eventually chooses to associate with the eNodeB with the best value. Vehicles communicate to the eNodeB using the up- and downlink interfaces. The sidelink interface is used when two vehicles want to directly communicate with each other. In the in-coverage mode of operation, the eNodeB manages the wireless resources and exchanges control information with the UE; however, the vehicle exchange application data directly via the sidelink [3, 2].

Out-of-coverage mode. In case road segments do not have cellular coverage, *Cellular V2X* enables vehicles to communicate autonomously with each other using the sidelink interface. The resource allocation mode is configured as unmanaged, where the UE dynamically selects its resources from a pre-defined pool of resources. We note that the received signal-to-interference-noise ratio (SINR) at the cell borders are also regions where vehicles can operate in out-of-coverage mode because the signal strength from the eNodeB might not be sufficient for reliable V2X communication. The decision to switch to the out-of-coverage mode on such road segments is determined by measuring the SINR, assessing the data traffic load and continuously monitoring the radio resource utilization of the wireless link.

3.3 Channel Modeling

Typical channel models consider multipath propagation and fading for narrow band radio communication where they assume that similar delays are experienced by the propagating waves; for example in *Artery-C*, Rayleigh and Ricean fading models can be applied. Additionally, the *Artery-C* simulator also incorporates the power delay profiles of multi-tap channel models specified by ITU including the pedestrian A / B and vehicular A / B channel models [5]. The power delay profiles along with the root mean square (RMS) delay spreads characterize the frequency selectivity of the channel. In V2X communication, the fast movement of the vehicles causes the channel to exhibit time variance (selectivity), which is further modeled as Jakes spectrum. While adhering to the abstraction at link level, we consider the transmit/receive power measured directly at the antenna terminals of base stations and UE.

While simplified channel models are sufficient to get an understanding of the overall statistics of vehicular communications, it is important to consider the geometrical aspects in order to study accurately the propagation characteristics in a complex vehicular network. Such approaches for geometry-based channel modeling can be classified into two categories – deterministic and stochastic.

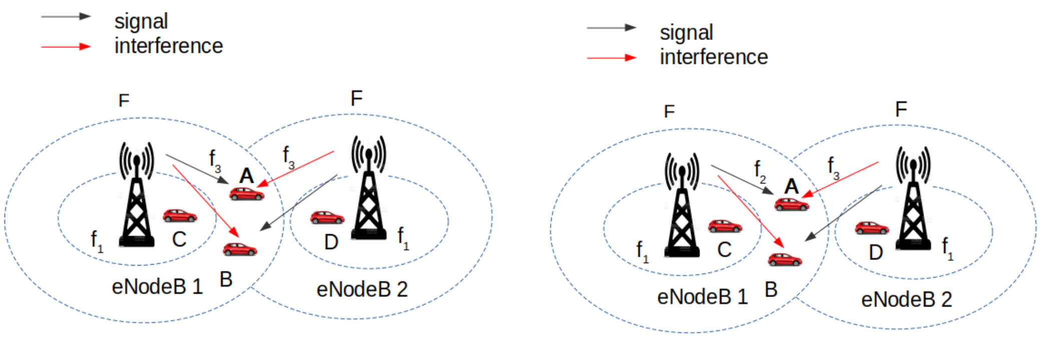
In the deterministic approach, the geometrical aspects of specific sites, including vehicles, buildings, terrain and foliage, are taken into account. Although this approach is advantageous in terms of accuracy, it consumes a lot of computational resources and the results are applicable only to that specific site or geographical area. In order to simplify the computation for larger scenarios such as *InTAS*, we consider a statistical approach to model the small scale and large scale fading/propagation characteristics. The Winner II channel model [8] is a good choice for geometry-based stochastic channel modeling, which considers both line-of-sight (LOS) and non line-of-sight (NLOS) wireless propagation conditions for various types of environments. Owing to non-homogeneity in the obstructions such as buildings, foliage and movement of vehicles in the crowded part of the city, we have considered it as a NLOS scenario where the path loss is calculated according to

$$PL = 44.9 - 6.55log(h_{BS})log(d) + 34.46 + 5.83log(h_{BS}) + 23log(f_c/5) \quad (1)$$

where h_{BS} is the height of the base station and d is the distance between transmitter and receiver for a given carrier frequency f_c.

3.4 SINR Model

In order to study the effects of multipath propagation in a densely crowded urban environment, we apply an SINR model which considers several factors, i.e., losses due to time-frequency selectivity of channel, thermal noise and inter-cell interference. For the out-of-coverage mode of *Cellular V2X*, we encounter only the effects of multipath propagation and thermal noise, but in the in-coverage mode, the effect due to inter-cell interference needs to additionally be taken into account.



(a) No inter-cell interference coordination (ICIC) (b) With ICIC

Figure 2: Modeling of inter-cell interference in the network simulator

Inter-cell interference occurs when users in neighbouring cells attempt to simultaneously use the same radio resources. This is caused by the fact that eNodeBs optimize the resource allocation for the UEs in their cell and are not aware of the allocation in neighbouring cells, which can be specifically harmful for UEs located at the border of overlapping cells: Figure 2a shows that although the vehicles C and D use the same frequency f_1, they do not experience any interference because they are located close to the base stations and hence use low transmit power. On the other hand, vehicles A and B experience interference on the same frequency

f_3. Figure 2b illustrates the use of inter cell interference coordination (ICIC), a standardized mechanism in cellular networks, where eNodeBs are tightly time synchronized and exchange information among each other about the resources utilized by their UEs. This helps to mitigate the interference problem caused by spatial reuse of frequencies.

4 Modeling Cellular Coverage in SUMO

The concept of vehicular networking has lead to the need to establish reliable communication between vehicles, infrastructure and other traffic participants. In addition to developing road traffic models in *SUMO* to model vehicle and pedestrian behaviour, there also arises a need to model network infrastructure. With a long term goal to study different application scenarios of *Cellular V2X* communication in the city of Ingolstadt, we hereby extend the *InTAS* scenario by modeling cellular coverage sites in one of the densely crowded area (the urban district *Ingolstadt Mitte*), which is a good choice for modeling an urban macro cell environment. Specific reasons to introduce the modeling of cell sites in a road traffic scenario are as follows:

- Get a clear understanding of the portions of the road covered by cellular network, i.e., which providers are operating, frequency bands, etc.
- Retrieve the number of vehicles currently served by a certain base station in a specific cell. This information is helpful to study the occupancy of a cell at a given time during the day and to further optimize the allocation of radio resources.
- Develop a better understanding of the cell coverage and interference characteristics at different points in a cell site, e.g., within the cell close to base station, near cell borders, overlapping regions etc.

The importance of having bi-directional coupling between the network simulator *OMNeT++* and the microscopic traffic model in *SUMO* is well explained in [15]. Continuing with the same architecture, the addition of the cellular layer helps us to generate a record consisting of mobility events (interactions between road traffic participants and eNodeBs) for routable entities such as vehicles and pedestrians that can be further utilized to analyse the vehicle behaviour, accuracy of message transmission & reception in case of events taken place in the recent past. In the following subsections, we further discuss about the structure of the cell sites, how to model them in sumo environment and also the types of antennas deployed.

4.1 Cell Sites

For modeling of the geographic environment and for defining the application scenario, we rely on [5], which defines detailed test environments for the evaluation of cellular networks, specifically for enhanced mobile broadband (emBB), ultra-high reliable and low-latency communications (URLLC) and massive MTC, namely *(i) indoor hotspot-emBB*, *(ii) dense urban-emBB*, *(iii) rural-emBB*, *(iv) urban macro-mMTC*, *(v) urban macro-URLLC*. These test environments correspond to the major application scenarios in the 3GPP specifications for 5G cellular networks and define define target key performance indicators for every scenario. In this paper, we have developed a *dense urban-emBB* test environment which is characterized by high density traffic load comprising of fast moving vehicles and pedestrians.

In the proposed cellular coverage layer in *SUMO*, each cell site comprises three transmission reception points (TRxP) that are placed in a regular hexagonal grid (Figure 3). A cell site is

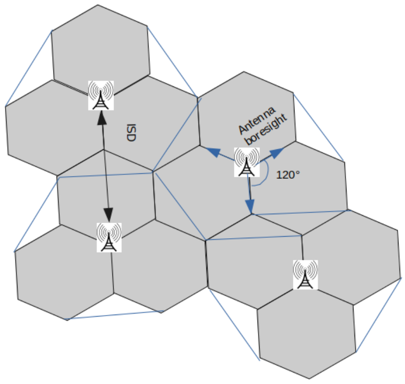


Figure 3: Dense urban macro cell layout

served by a base station (eNodeB) covering three cells in the sector at an angle of 120 degrees. The transmitter-specific parameters are defined in Table 1. We note that the inter-site distance (ISD) is 500 m for an urban macro cell. A screenshot of the cell sites in *InTAS* is depicted in Figure 4.

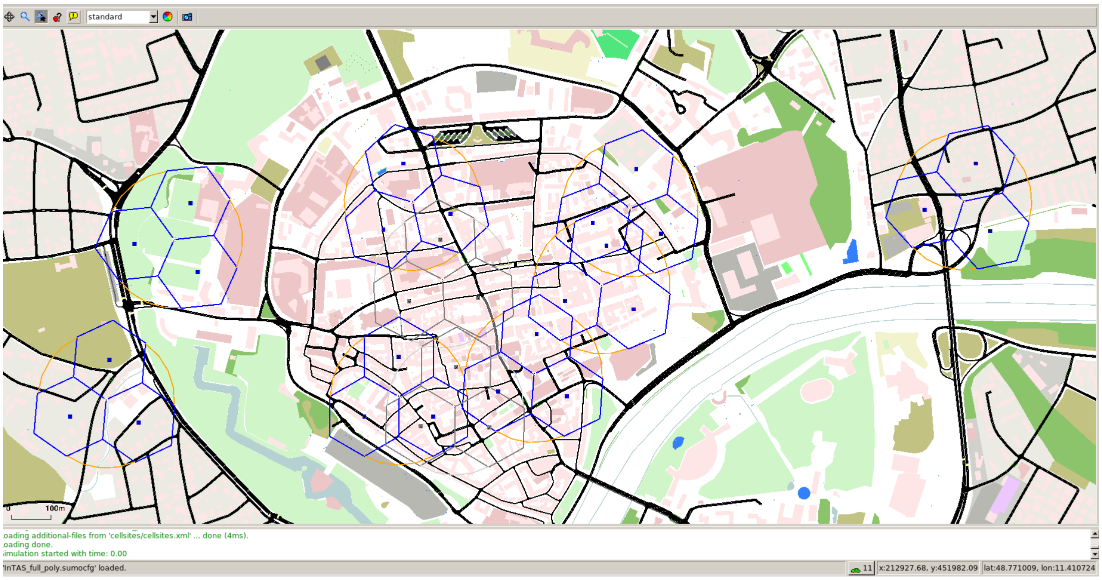


Figure 4: Cell sites in the *SUMO* Ingolstadt traffic scenario *InTAS*

4.2 Generation of Cell Sites in SUMO

The workflow to create cell sites in a *SUMO* scenario is illustrated in Figure 5, using *InTAS* with `Ingolstadt.net.xml` as an example. In general, the process of modeling cellular coverage involves the following aspects:

- Definition of eNodeB as a `Point-of-interest (POI)`. The geospatial coordinates of the eNodeBs (latitude, longitude) are obtained from the crowdsourcing database *Cellmapper*.[2]

- Creation of a hexagonal layout (Figure 3) utilizing the `polygon` feature in *SUMO*: With the knowledge of the coordinates of eNodeB, we obtain the vertices of the hexagonal grid.
- Creation of boundaries to distinguish different areas such as cell borders and sectors: this helps to distinguish among the lanes having varying degrees of cellular coverage.
- Assigning attributes to eNodeB and the corresponding cells in a `.xml` file.

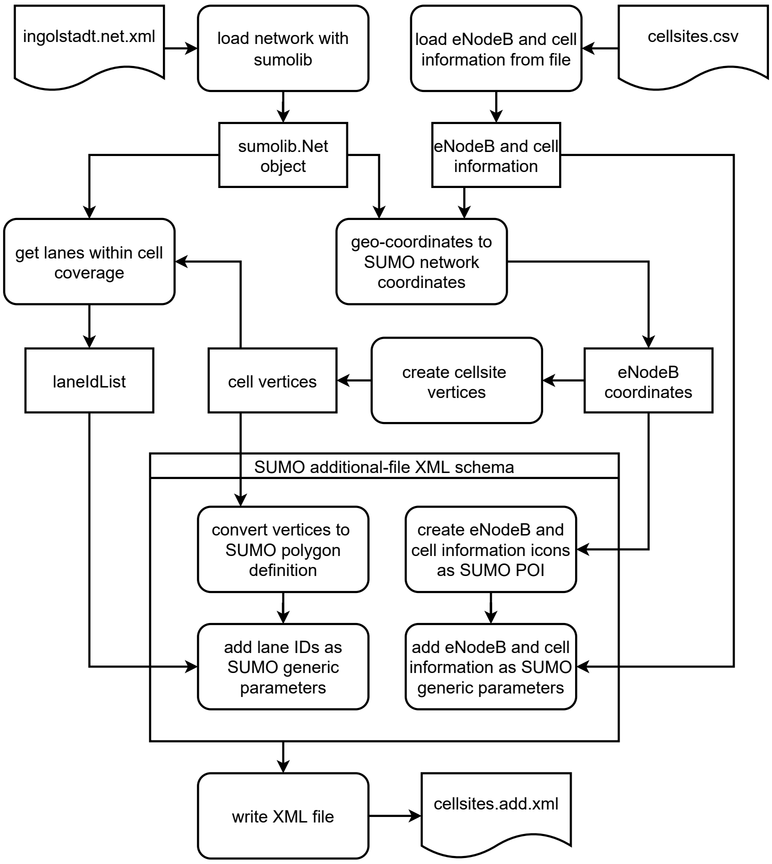


Figure 5: Workflow for the creation of cell sites

In Figure 5, the first step is to create a cell information file (`cellsites.csv`) that consists of the base stations and cell related attributes (refer to Figure 6a and 6b) . Then, we convert the geospatial coordinates of the eNodeB into *SUMO* recognizable network coordinates. The logic for the generation of cell vertices is written in a separate `Python`-based script, which takes the coordinates of the eNodeB as an input parameter and generates the cell site vertices to construct the hexagon grid (`polygon`) inside `Ingolstadt.net.xml` file. We use different colors to indicate the cells, cell boundaries and sectors. We add the lane IDs of the lanes traversed by the hexagonal cells as generic parameter because later this information is useful to obtain

[2] https://www.cellmapper.net

the details of the vehicles, which are inside the cellular coverage area and their mobile event log details w.r.t to the eNodeB. The eNodeB and cell information is subsequently written into the `cellsites.add.xml` file, which gets loaded along with the `intas.sumocfg` file during the start of simulation. This workflow allows the user to include any number of attributes possible in the `cellsites.csv` file, generate the hexagon grid of appropriate cellular environment and automatically generate the `cellsites.add.xml` file.

A screenshot of the specific parameters of the eNodeB and cells inside the *SUMO* environment is shown in Figure 6a and 6b respectively. In order to retrieve these attributes into the network simulator, we use the `TraCI` interface in the `POI` scope.

In order to determine the data traffic load in each cell, we first retrieve the list of lane IDs traversed by the polygon and subsequently obtain the list of vehicle IDs present in that lane. Since vehicles can dynamically enter and exit the cellular coverage region, it becomes important to monitor the road traffic flow in order to get an idea of the number of users (vehicles, pedestrians, etc.) connected to a given base station and the radio resources utilized by the users in the particular cell site.

4.3 Antenna Characteristics

Base station (BS) antennas are modeled having one or multiple antenna panels, where an antenna panel is composed of one or multiple antenna elements placed vertically, horizontally or in a two-dimensional array. An antenna panel has $M \times N$ antenna elements, where N is the number of columns and M is the number of antenna elements with the same polarization in each column. The $M \times N$ elements may either be single polarized or dual polarized.

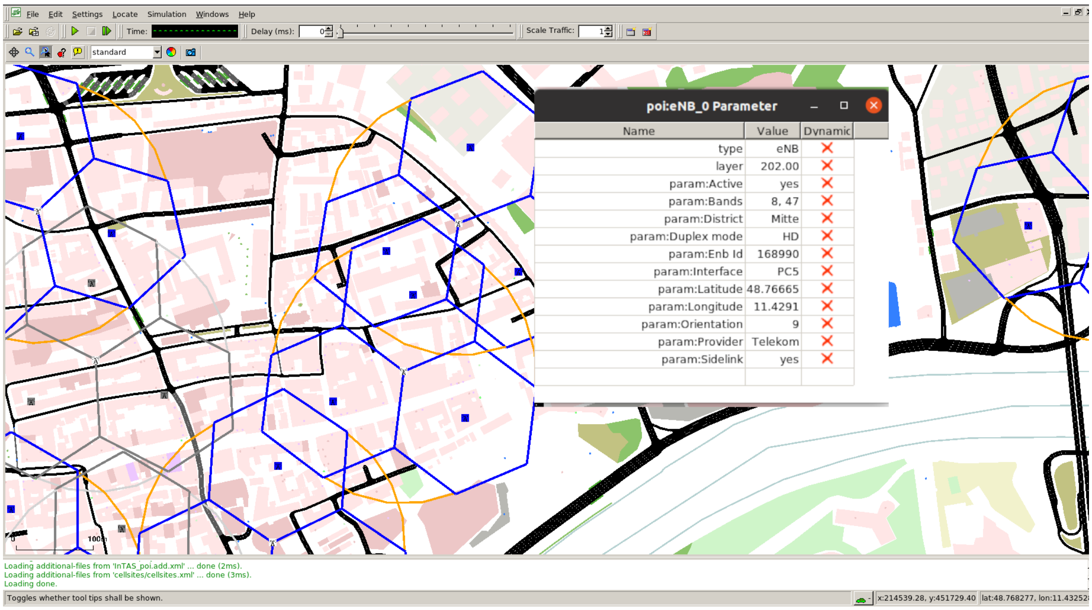
The antenna bearing is defined as the angle between the main antenna lobe centre and a line directed due east given in degrees. The bearing angle increases in a clockwise direction. Figure 5 shows the hexagonal cell and its three TRxPs with the antenna bearing orientation proposed for the simulations with three TRxP sites. The centre directions of the main antenna lobe in each TRxP point to the corresponding side of the hexagon. The antenna parameters for base station and end devices, i.e., eNodeB and UE, are listed in Tab. 1.

Table 1: Antenna-related simulation parameters

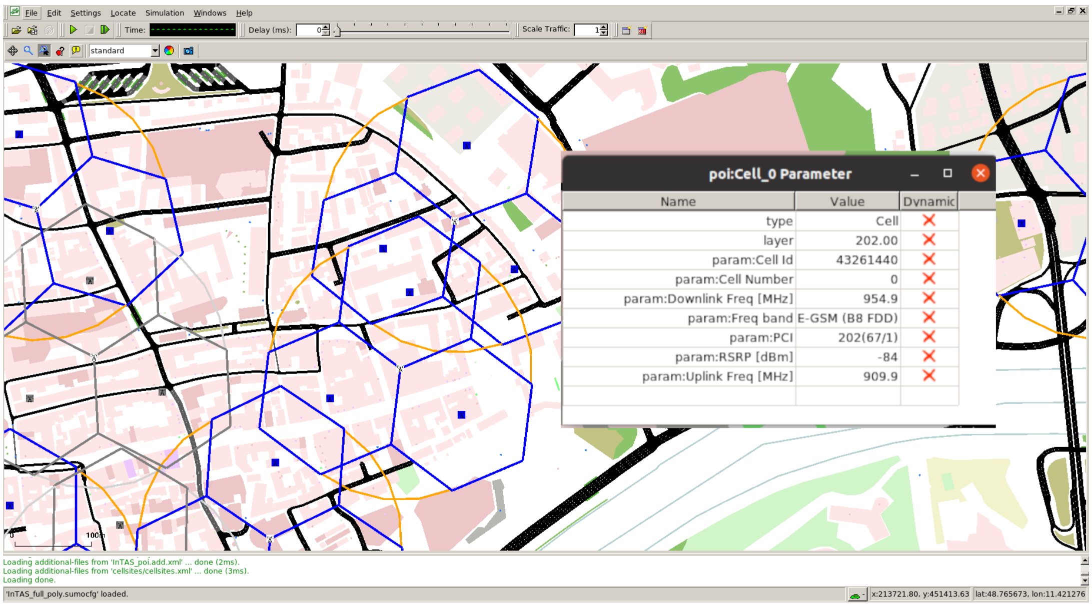
Parameter	**Equippment**	
	eNodeB	UE
Antenna gain [dBi]	18	0
Antenna profile	Omnidirectional and anisotropic	
Height [m]	25	1.5
Configuration (Tx, Rx)	$4X4$	$2X4$
Noise figure [dB]	7	5
Thermal noise level [dBm/Hz]	-174	
Mobility model	Stationary	Dynamic
Transmission bandwidth	20MHz, FDD	

4.4 Cell Association and Handover

When the vehicles enter the regions of cellular coverage, they associate with the appropriate base station dynamically by taking into account of two factors, namely *(i)* the distance from the



(a) eNodeB specific parameters



(b) Cell-specific parameters

Figure 6: Cell site-related simulation parameters of the cellular coverage layer in *SUMO*

base station and *(ii)* the received signal strength on the downlink interface. The vehicle attaches to the closest base station that has the highest received signal strength indicator (RSSI) value. The test environment shown in Figure 4 supports simulating the mechanism of handover using the direct interface among eNodeBs. In Figure 4, we can use different colors to depict the cells of different operators (e.g., blue color for Telekom and grey for Vodafone). The eNodeB and the cell-specific parameters are periodically retrieved from the simulation as the vehicles move from one cell to another. It is observed that in regions of overlapping cells and along the borders, the handovers are reported to be more frequent.

5 Proof-of-Concept

In order to extend the *InTAS* scenario for *Cellular V2X* communication, we have simulated a V2V sidelink broadcast communication network, in which both the sidelink modes – in-coverage and out-of-coverage – are operational and a vehicle can dynamically switch between these modes based on the availability of cellular network coverage. In the first step, we develop an SINR coverage map and further evaluate the impact of different types of interference in a given cellular network coverage area.

5.1 Vehicular Network Model

In the scenario, the road traffic flow with cars, buses and other vehicles is modeled according to the routing optimization methodology presented in the original *InTAS* scenario [10]. We set the speed of the vehicles to be in the range of $20 - 50$ km/h and do not consider pedestrian and other slow moving traffic. The smallest unit of simulation step is one millisecond, which corresponds to one transmit time interval (TTI)/subframe in the 3GPP standards for LTE. The simulation parameters related to the vehicular network model are listed in Table 2.

Table 2: Simulation parameters related to the vehicular network model

Use case	V2V sidelink broadcast
Mobility	Both Tx and Rx are moving
Interfaces	Up-/Downlink U_u and sidelink PC-5
Velocity [kmph]	20 to 50
Sidelink modes	In-coverage (mode 3) & out-of-coverage (mode 4)
Mode switching	Up-/downlink ↔ sidelink (in-coverage), in-coverage ↔ out-of-coverage
Carrier frequency	V2I: 5.9 GHz, V2V: 5.9 GHz
Channel model	Winner II
Selectivity	Time-frequency selective
Inter-cell interference	Only in-coverage mode

When a vehicle is located inside the region of cellular coverage, previous studies [4, 3] have shown that in-coverage mode is the preferred mode for sidelink communication. The reliability of packet reception is influenced by the quality of received signal strength from the associated base stations. The first step of validation aims at analyzing the received signal strength for an UE at various locations in a cell site – within the cell (inside the hexagon borders), at the cell borders and in the areas of overlapping cell borders. The factors influencing the signal-to-interference-and-noise-ratio (SINR) are distance between transmitter and receiver, multipath propagation and fading effects and inter-cell interference.

Based on the antenna characteristics for a single element antenna configuration and the chosen pathloss model from Winner II, we generate an SINR map as shown in Figure 7. We can observe that the regions with the maximum signal strength are the places in close proximity to the base stations along the antenna boresight angle. The red and the orange regions of the map indicate a value of SINR of around 10 to 15 dB. The blue shades correspond to areas with SINR in the range of 5 dB to -5 dB. The areas without any color on the map represent regions where SINR is below -5 dB threshold.

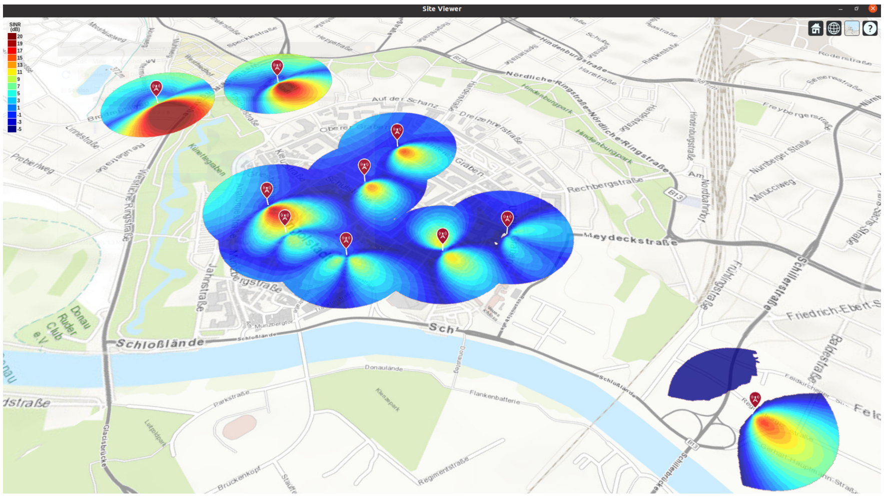
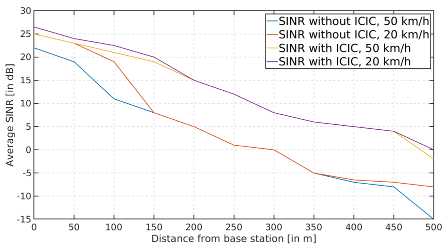
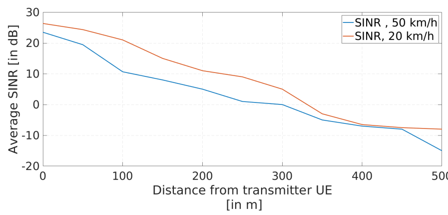


Figure 7: SINR for a single antenna element



(a) In-coverage mode



(b) Out-of-coverage mode

Figure 8: SINR analysis for sidelink modes for different vehicle speeds and considering ICIC

Based on the data collected from simulations, we generate plots to study the effect of SINR in the presence of Doppler shifts for both sidelink modes considering the boundary conditions listed in Table 2. For in-coverage operation, the vehicle has to associate with the base station and obtain radio resources for sidelink communication. The uplink (UL), downlink (DL) and sidelink (SL) SINRs play a significant role in the calculation of SINR for the in-coverage operation. The results in Figure 8a indicate that as the distance from the base station increases, the SINR experienced by the vehicles starts degrading. Especially at distances greater than 400 m, the vehicles experience inter-cell interference caused by neighbouring base stations. The overlapping of the cellular sites can be observed in Figure 7. When there is no inter-cell interference coordination (ICIC) employed, we observe that SINR reduces as low as -15 dB thereby making it difficult to associate with the base station and establish communication with other vehicles. By employing suitable ICIC mechanisms as proposed in *SimuLTE* [16] we observe the average SINR to be around -8 dB as indicated in Figure 8a.

In out-of-coverage mode as depicted in Figure 8b, the effects of inter-cell interference is not applicable. Here, we refer to the SINR computed on the sidelink interface in a V2V broadcast scenario. By taking the average value of SINR experienced by the receivers of the sidelink broadcast, we observe that when the distance between transmitter and receiver vehicle is greater than 400 m, the average SINR at the receiving vehicles is reported to be around -15 dB for vehicle speeds of 50 km/h and around -8 dB for vehicle speeds of 20 km/h. Although the effects of inter-cell interference does not come into discussion for the out-of-coverage mode, owing to losses due to multipath propagation in a dense urban environment with many obstructions such as buildings, bridges, signboards etc, the quality of SINR is highly affected.

For an UE moving along the cell borders, it becomes a difficult decision to whether continue operating in the in-coverage mode or switch to out-of-coverage mode because it is difficult to associate with eNodeB owing to bad link quality (low SINR). By carefully examining certain factors like distance from the transmitter, latency requirements of the V2V message and resource pool availability for both the modes, the mode switch decision has to be accomplished.

6 Conclusion

In this paper, we have presented a first approach to natively model an urban macro cell environment in *SUMO*. Unlike other approaches for coupling network simulators with *SUMO*, we have introduced a cellular coverage layer in *SUMO*, which enables *SUMO* to be aware of the cellular coverage and the link quality. The presented solution comprises a set of scripts to generate the hexagonal grid and files with details of base stations, cells and providers. We have added base station- and cell-specific parameters as attributes, which help to simulate different aspects of V2X communications such as cell association, handovers, radio resource monitoring, allocation, and utilization. We have coupled the *Cellular V2X* network simulator *Artery-C* with *SUMO* enhanced by the cellular coverage layer. *Artery-C* realizes different types of stochastic channel models which accurately calculate the SINR at various regions of the cellular grid. Having studied a *dense urban-emBB* test environment in this paper, the scripts developed for the generation of the hexagonal grid layout can be easily refactored to model other cellular test environments such as *rural-emBB* and *urban macro-mMTC*. Also, they can be directly applied to other existing *SUMO* road traffic scenarios. Last but not least, the proposed method can model other types of network infrastructure than LTE or 5G as in this paper such as WLAN. The cellular coverage layer in *SUMO* enables new ways for simulating microscopic road traffic by directly incorporating cellular networks as a integral part of the road traffic infrastructure comparable to traffic lights.

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