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A top–down approach for building realistic reference scenarios and simulation framework for LTE C-V2X communications

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ABSTRACT

Many vehicle-to-everything (V2X) applications and use cases require their feasibility to be simulated, tested, and validated in realistic traffic scenarios and under various network conditions before real-time testbed implementation. As cellular-V2X (C-V2X) becomes a superior technology for future connected and autonomous vehicles, the need for a simulation framework, which integrates traffic and network simulators with a realistic channel model, becomes more evident. The challenge is to overcome existing simulation platforms' weaknesses and improve simulation results' accuracy while preserving flexibility with manageable implementation complexity. This paper proposed a top–down approach for building reference scenarios with macroscopic and microscopic layers, which interweaves traffic, network, and channel simulators. The basis for the proposed simulation framework is realistic scenario data, which provides the input to the road traffic simulator and the radio channel simulator. The core of the whole simulator is the network simulator interacting with the two other simulators via dedicated interfaces. The road traffic simulator generates the vehicles' positions and is forwarded to the network simulator, which requests the radio channel simulator for the path loss values on the transmitter–receiver (TX-RX) link. As a proof of concept, the simulation results focused on the load and interference analysis in the absence and presence of V2X traffic.

1. Introduction

Reliable and low latency communication are necessary for the automotive industry's move from connected to connected and autonomous vehicles (CAV) [1]. A multitude of radio access technologies exist for providing wireless connectivity between vehicles, i.e., vehicle-to-vehicle (V2V), and among vehicles and the roadside units (RSUs) attached to the transportation infrastructure, i.e., vehicle-to-infrastructure (V2I), vehicle-to-pedestrians (V2P) and Internet, i.e., vehicle-to-network (V2N) [2]. It includes IEEE 802.11p [3], and its successor IEEE 802.11bd [4] enabled direct short-range communication (DSRC) [5], or cellular vehicle-to-everything (C-V2X) [6] based on Long Term Evolution (LTE)/4th Generation (4G) or 5th Generation (5G) mobile networks by 3rd Generation Partnership Project (3GPP). It is even deemed necessary to evaluate and validate the capabilities of these standards in realistic traffic scenarios and different use cases under various network conditions. Most of the research relies on either real-time testbed implementation or simulation-based studies. While testbed implementations are more accurate than simulations, they incur a substantial cost and are less scalable. Whereas in simulation-based studies, lower cost and scalability are achieved at the cost of less accuracy [7]. For feasibility analysis of emerging concepts, protocols, and architecture and use cases that are not mature enough are always good candidates for simulation-based evaluation first, before the full-fledged testbed implementation.

Simulation platforms are widely used to evaluate DSRC and cellular technologies and are essential to developing future vehicular networks. For DSRC, most research papers deal with coupling the traffic simulators with the network simulators to get insight into the interdependencies between the communications and transportation systems. Whether combined through a standard interface between the two or embedded into each other, they lack accuracy in modeling the realistic vehicular environment and channel characteristics. In the context of cellular networks, a majority of simulation platforms implement 3GPP compliant models for direct V2V communications, i.e., LTE/4G (Mode 3 and 4) [8] and 5G New Radio (NR) (Mode 2) C-V2X [9]. However, little work is available that primarily focuses on V2I or V2N simulation platforms. These simulation platforms rely on pre-existed communication modules built into the network simulators and do not include a

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detailed simulation of a vehicular radio channel. They often make gross simplifications and assumptions regarding realistic cellular network deployment, cellular traffic intensity map-based background traffic, interference caused by static and mobile users, and inter-cell interference. Incorporating these details and improvements in a single universal simulator comes with its computational and memory resources cost. Moreover, such integration causes extensive modifications and generalization in control and management functionalities, inflexibility, and higher implementation complexity.

Several features of the network itself and the surrounding environment and user behavior (both static and mobile) need to be taken into account to achieve a realistic system-level evaluation of the cellular (C-V2X) network. Towards this end, a top–down approach toward building reference scenarios and simulation framework are proposed [10,11]. The framework operation comprises two layers, i.e., *macroscopic* and *microscopic* interweaving traffic, network, and radio channel simulators. The macroscopic layer combines static and environmental data from various sources such as 3D building geometry, road network layout, and land-use class information such as buildings, green spaces, commercial, etc. The data derives important network characteristics such as spatial–temporal variations of the cellular data network and user location distribution. The macroscopic layer includes a realistic deployment of an LTE network and the generation of time-varying traffic intensities. The microscopic layer comprises fine-grained details of the site-specific environment by further refining the macroscopic reference scenarios. The microscopic layer covers vehicular mobility traces, distribution of individual background users, inter-cell interference, and use-case-specific configurations.

The main contributions of this paper are:

1. The data from multiple sources such as digital elevation maps, land usage information, and 2.5D/3D building geo-data are utilized, and emulated LTE network at 800 MHz is planned to achieve realistic network coverage. The antenna positions and orientations are planned using publicly available data and refinements through drive tests/measurements. As a result, a macro-cellular network consisting of 48 sites with 133 sectors operating at 800 MHz is set up for the whole planned area of 10 km × 16 km.
2. The background data traffic in the network depends on users' position and activity, which changes over one day. A process is defined to generate realistic traffic intensity maps that reflect the average user behavior and location, which vary throughout the day. The variation of the user activity is modeled by user activity patterns, which are modified according to the typical situation in Doha, Qatar. The spatial traffic distribution is modeled using the user distribution over different land-use classes for the working days and weekends.
3. In the proposed framework, the radio channel simulator can be substituted depending on the specific system to be simulated to foster flexibility among the simulators in the toolchain. Thus, emulating different data channels and analyzing the resulting system behavior is possible. Besides deterministic channel modeling utilizing ray-optical modeling, the proposed can also be used with stochastic channel models of typical vehicular scenarios.
4. It includes the details on the pathloss prediction module that considers different land-use classes and user demand while calculating signal-to-interference and noise ratio (SINR) and network load. It also includes details of downlink and up-link system-level simulators for LTE. For this purpose, we have utilized the Simulator for Mobile Networks (SiMoNe) [12].
5. The proposed simulation framework has been tested to evaluate the impact of load and interference analysis. Earlier, the simulation model was applied for testing and evaluation of both IEEE 802.11p and 4G/LTE link-level performance evaluation [10, 11], the interconnection of IEEE 802.11p and LTE system-level simulators, and the development of hybrid solutions including algorithms for the selection of the transmission technology and traffic steering or offloading [13].

A detailed performance evaluation study is performed for various parameter settings such as downlink (DL) and uplink (UL) load with both background and vehicular user traffic to evaluate the LTE by 3GPP communication standards in a vehicular networking environment. An LTE system-level simulation of 36 traces representing 144 vehicles in a 2 km × 2 km scenario is presented. The vehicles with equal traffic demand for the uplink and downlink share radio resources with regular LTE users. The simulation has pointed out that the uplink cell load can quickly change into an overload state since the position of a user highly affects the uplink interference of users in nearby cells. Finally, the simulation has shown that an LTE cell can handle 68 vehicles next to general background traffic during the busy hour before the uplink cell capacity is exceeded.

The remainder of the paper is organized as follows: Section 2 explains the state-of-the-art simulation platforms for DSRC-enabled V2X and Cellular-V2X (C-V2X) communication and their limitations. Section 3 presents a top–down approach to building reference scenarios. It includes an overview of the different data sources and a detailed explanation of the constituent building blocks of the macroscopic and microscopic layers. Section 4 includes the details in downlink and uplink system-level simulations. Section 5 describes the system-level simulations for one scenario focusing on load and interference analysis. Section 6 concludes the paper with a summary and provides an outlook on future work.

2. Related work

For several years, researchers have sought ways to increase the efficiency and improve the scalability of simulation tools for V2X communication without compromising accuracy. This section provides an overview of different simulation platforms and tools for the performance evaluation of V2X communications.

2.1. Simulation platforms for DSRC enabled V2X

Initially, the focus was on the integration of vehicular road traffic generation tools like the simulation of urban mobility (SUMO) [14] and VISSIM [15] and network simulators such as ns-2/ns-3 [16], OPNet [17] and OMNet++ [18]. The integration can take one of the two *offline* and *online* forms. In the *offline* case, the coupling between the traffic and network simulators is *unidirectional*, i.e., for the given simulation scenario, the traffic simulator is run first, generating the required mobility traces in a widely recognized format such as floating CAR data (FCD). The next step is the conversion of traces into the format acceptable by the given network simulator. Finally, the network simulator reads the movement traces of individual vehicles from the static files and executes the packet-level simulations. While the unidirectional approach offers the flexibility of choosing a variety of different simulators, it cannot capture and control the behaviors of vehicles as required by the communication system during runtime. Similarly, the communication protocol can also adapt its functionality due to transportation incidents such as traffic accidents.

The Veins [19] framework implements the *online* case utilizing an intermediate interface between the SUMO and OMNet++ simulators named traffic control interface (TraCi). TraCi allows *bi-directional* coupling where traffic and network simulators act as TraCi-Server and TraCi-Client, respectively, and exchange messages over the transport control protocol (TCP) connection. The framework supports the IEEE 802.11p and IEEE 1609.4 DSRC or wireless access in vehicular environment (WAVE) network layers. While Veins can evaluate complex vehicular ad hoc networks (VANET) scenarios like accidents and the impact of the vehicular application on traffic patterns, the framework can simulate a small-scale network only. Several factors, such as the number and type of TraCi function calls and computation cost, significantly slow the simulation speed. Many other simulation platforms integrate traffic and network simulators coordinated by a control module or interface in the middle. For example, iTETRIS [20] extends and integrates SUMO and ns-3 with the iTETRIS control system (iCS) as the central coordinating entity. The vehicle2-X simulation runtime infrastructure (VSimRTI) [21] platform implements interfaces that couples SUMO and VISSIM, JiST/SWANS, and mapping tools. Other notable platforms include highway traffic simulator (HiTSim) [22], traffic and network simulation environment (TraNS) [23], vehicular networks simulator (VNS) [24], vehicular network-integrated simulator (VNetIntSim) [25], and integrated distributed connected vehicle simulator (IDCVS) [26].

Emulating a realistic vehicular environment and integrating traffic, network, and channel simulators into a single, universal tool is impossible because of its higher implementation complexity and lower flexibility. Some simulation frameworks combine a toolchain of different simulators to investigate the performance of different vehicular communication technologies [27,28]. The implementation complexity is managed by extracting and sharing the outcome of one simulator with the following simulators in the toolchain. The proposed simulation frameworks employ an offline interface to combine the road traffic, radio channel model, and network simulators.

Most network simulators described earlier focus on the simulation of DSRC-enabled IEEE 802.11p or IEEE 802.11-enabled Wi-Fi communication standards for V2X communication. Several of these simulators assume gross over-simplified channel models or employ easily implemented and computationally efficient analytical models at the physical layer. Improvements at the physical layer often result in a considerable increase in computational time and the necessary memory resources. The scalability in the number of participating vehicles during an experiment is achieved at the cost of accuracy. The performance does not account for the impact of static and mobile objects surrounding the communicating vehicles. Moreover, the simulation platform supports pre-existing radio access technologies (RATs) bundled as extra modules with the network simulator. The approach often requires simplifying wireless control and management functionalities and extensive modification to the coordinating entity to support new RAT modules.

2.2. Simulation platforms for LTE C-V2X

With wide-scale vehicle deployment of C-V2X well underway, there is an increasing need for testing and verifying C-V2X communication system performance and functionality. While field trials in the real-world environment are costly, time-consuming, and challenging, simulation-based studies are needed to evaluate and validate compliance with the standards during the initial trials. For this purpose a number of research projects and research initiatives are geared towards developing LTE C-V2X such as V2XSim [29], ConVeX [30,31], C-V2XSim [32], CarLink [33] and OpenCV2X [34].

The V2XSim [29] simulator utilizes a Gazebo-based robot simulation engine [35] to precisely emulate different physical mechanics, including the control algorithms and communications. The communication is performed via the Virtual Roadside Unit, which acts as the base station to collect and relay the important safety messages (BSMs) among the connected vehicles and other destinations. The simulator implements a small-scale vehicle-to-network-to-vehicle (V2N2V) and V2N communication scenario. It uses a simulated world with 3D models to emulate the real-world environment surrounding the vehicles. The ConVeX [30] project is a consortium of leading automotive, telecom, and academic institute to deploy a real-world testbed and carry out Cellular-V2X (C-V2X) field trials based upon the 3GPP Release 14. The research projects also include the development of simulation tools [31] to test and validate the hybrid use cases that are not mature enough for the testbed deployment. It includes developing standard function components such as traffic and network simulators, performance evaluation, modeling, and quantitative analysis that could be used to investigate emerging topics such as network slicing, spectrum management, context awareness, etc.

The C-V2XSim [32] simulator is being developed at the Fraunhofer Institute for Integrated Circuits (IIS), Germany. C-V2XSim is a web-based, end-to-end system-level simulation tool that analyzes various C-V2X communication-related performance metrics such as reliability, throughput, and latency. Currently, C-V2XSim supports V2N communication for the remote driving scenario. It includes realistic distribution of base stations, different urban scenarios, and human-driven and remotely driven vehicles with varying speeds and visualization. The platform supports both IEEE 802.11p-enabled short-range communication and LTE-based long-range cellular communication. The CarLink [33] platform mainly consists of two components vehicle under test (VUT) and an external world emulator (EWE) with a targeted use case of advanced driver assistance systems (ADAS). The VUT component is hardware-in-the-loop (HiL), with a dual-interface enabled communication unit, an ADAS control unit, and an interface to EWE. The EWE is responsible for emulating the virtual environment surrounding the VUT. It includes a traffic simulator, wireless connectivity management, and an interface to connect to the ADAS subcomponent of VUT.

The Veins framework is also integrated into SimuLTE [36,37] via the INET framework, allowing cellular communications in the vehicular networking environment. The open cellular vehicle-To-everything (OpenCV2X) [34] platform extended the Veins framework and implemented a full-stack, open-source 3GPP compliant C-V2X Mode 4. Authors in [38] couples CarMaker and ns-3 to simulate the 3GPP Release14 C-V2X Mode 4 standard. The CarMaker traffic simulator creates a simulation environment, including a road scenario and vehicle model. At the same time, the ns-3 existing module on the LTE device-to-device (D2D) LTE-D2D module is extended to implement the C-V2X Mode 4 communication. The simulation model proposed in [39] achieves scalability by incorporating an analytical communication model of the direct C-V2X standard in the INTEGRATION traffic simulator. Most C-V2X simulation platforms implement 3GPP-compliant direct C-V2X modes for V2V communication, with little work on V2I or V2N communication. The simulation framework proposed in [40] relies on existing communication modules such as LTE, IEEE 802.11p, and C-V2X that are built for the network simulator ns-3.

The simulation frameworks described above made a gross approximation of the environment surrounding the communicating vehicles. For small to medium-scale cellular networks, scalability and simulation efficiency is achieved by employing simplified vehicular channel models, unrealistic cellular network deployment scenarios, and time-varying user distribution. Moreover, integrating a network simulator or analytical communication model into the traffic simulator often leads to inflexibility in choosing the right tools for the given simulation scenarios and increasing simulation complexity. Table 1 summarizes the most relevant simulation platforms and frameworks and compares them against the foremost desirable characteristics.

The proposed simulation framework allows,

- We incorporate detailed and realistic reference scenario information such as road traffic, vehicular mobility, and building and foliage object outlines.
- We evaluate given simulation scenarios using realistic data concerning topology/digital map, cellular LTE network deployment, traffic intensity based on daily user behavior, spatial traffic distribution, and static users with background data traffic.
- We provide an ability to simulate with easy parameterization of the use cases. For instance, users can adjust the number of participating vehicles, traffic generation and configuration, different communication network link-level models, and other use case-specific simulation parameters such as packet size, network load, and application quality of service (QoS) requirements.

Table 1
Comparison of the proposed simulation framework against the most relevant simulation platforms.

Simulator	Proposed	iTetris	ConVeX	CarLink	OpenCV2X	CarMaker	Integration
Characteristics		[20]	[30]	[33]	[34]	[38]	[39]
Link or System-level	Both	System-level	System-level	System-level	System-level	System-level	System-level
Simulation Scale	Large-scale	Large-scale	Small-scale	Small-scale	Small-scale	Small-scale	Large-scale
Visualization	Yes	Yes	No	No	No	No	Yes
Traffic Simulator	SUMO	SUMO	NA	SUMO	SUMO	CarMaker	INTEGRATION
Network Simulator	SiMoNe, analytical model, 3D ray tracer	NS-3	Analytical model	Analytical model	OMNET++	NS-3	Analytical model
Communication Standard	802.11p, LTE, and 5G C-V2X	802.11p, WiMAX, and UMTS	C-V2X Mode 3	802.11p, side-link (C-V2X)	C-V2X	C-V2X Mode 4	C-V2X (Direct)
Parameterization of simulations setup	Full	Partial	Partial	Partial	Partial	Partial	Partial
Selectable & realistic deployment scenarios	Yes	No	No	No	No	No	No

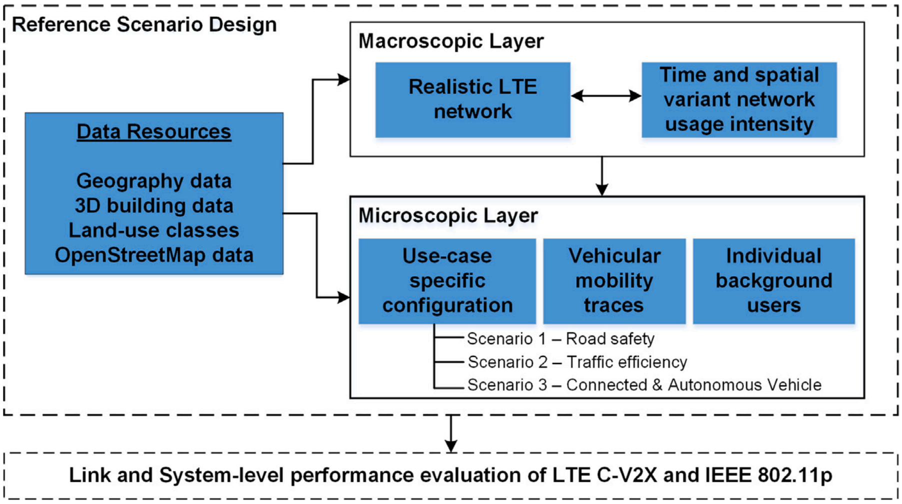

Fig. 1. Reference scenario design concept as a top–down approach.

- A user can select different reference scenarios. Examples include reference scenarios at downtown, highways, open spaces, and narrow or wide urban areas with many different simulation settings.

3. Top–down approach for building reference scenarios

One fundamental step towards the next-generation vehicular communication system is the performance evaluation of existing and emerging communication standards and technologies. Therefore, a comprehensive and well-defined set of reference scenarios is needed to develop algorithms, protocols, and, ultimately, a hybrid system architecture for vehicular environments. Multiple network characteristics, environment, and user behavior must be considered to allow realistic modeling of LTE C-V2X system-level behavior in simulations. As depicted in Fig. 1, a top–down approach is chosen for the scenario design to meet these requirements.

The top–down model uses two different layers of abstraction to describe scenarios, namely *macroscopic scenarios* and *microscopic scenarios*. The macroscopic layer aims at assembling different kinds of static, environmental (e.g., geo and building) data for a selected area. Within this area, multiple algorithms are applied to derive appropriate models for time and space-variant network usage intensity (i.e., telephone traffic) and user location distributions on a map basis. A realistic cellular LTE network is planned based on the information about the topology and building and the expected usage intensities. The second layer of abstraction, referred to as microscopic scenarios, further refines the scenario description for selected detail areas within the corresponding macroscopic scenario. For that purpose, the mobility aspect of (vehicular) users is modeled not by usage intensities that vary over time and space but by the trace-based movement of individual users, with each user offering a specific data demand to the network. The surrounding areas outside the microscopic scenario and non-V2X data traffic in the scenario can be modeled by map-based background traffic to take the effect of realistic inter-cell interference into account. Microscopic scenarios are thus intended to be designed with various characteristics to sufficiently represent diverse road traffic situations and allow the demonstration of different potential V2X applications and use cases. The detailed design approach is described more detailed in the following subsections.

3.1. Data resources

The development of the reference scenario is based on a multitude of environmental data for the area of approximately 14 km × 10 km in Doha, Qatar. The data was purchased from a specialized company [41] and is described in this subsection.

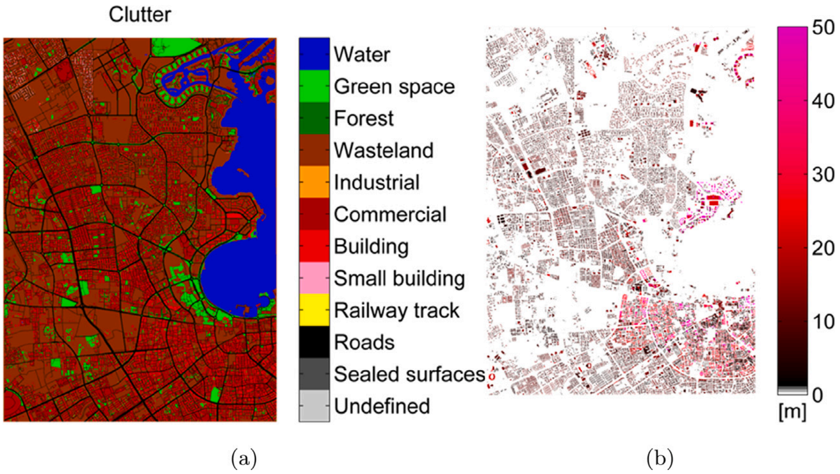

Fig. 2. (a) Land usage mapped to the categories used for telephone traffic distribution. (b) Building height (m) information.

Table 2
LTE Network Parameters used for the planning process.

Network parameters	Values
Carrier Frequency	800 MHz
System Bandwidth	10 MHz
Antenna Type	Kathrein 80010306
Transmit Power	46 dBm
Cell Load	100% (max. interference)

3.1.1. Digital elevation map

Terrain height information is used for the detailed ray-optical pathloss predictions ("ray tracing") in the use-case-specific scenarios. In the case of the considered region in Qatar, the terrain height varies only in the order of 10 m over a distance of several km. It, therefore, does not affect the investigated signal propagation in a meaningful manner.

3.1.2. Land usage information

There are several land-use classes, such as buildings, forests, and wasteland, as illustrated in Fig. 2(a). The information on the land-use classes is used to achieve a realistic layout of the planned LTE network. The information is used as an indicator for the telephone traffic intensity stemming from the different land-use classes and, thus, the required density of the serving cellular network. In subsequent subsections, detailed information on the mapping process of telephone traffic to the land-use classes is given.

3.1.3. Building height information

Building data in a vector representation of each building with accompanying height information is available for the selected part of Doha, Qatar. In conjunction with publicly available satellite images, the building information is used to position cellular network antennas and calculate the ray-optical pathloss propagations. For this, accurate building information is essential, as it dramatically impacts the coverage area of a base station antenna. Fig. 2(b) shows the available building data, which aligns with the publicly available satellite images, e.g., GoogleEarth [42].

3.2. Developing the macroscopic-layer

Macroscopic scenario development has two main aspects: planning and refining a realistic LTE cellular network and traffic intensity generation.

3.2.1. Planning a realistic LTE cellular network

Based on the data described in the previous section, a realistic LTE network at 800 MHz is planned to achieve realistic network coverage. No mobile network operator (MNO) is participating in the project, so the antenna positions and orientations were planned using publicly available data. As a starting point for network planning, some assumptions on the network density and expected user traffic were made. On-site visits and drive tests later refined the planned network. Once the network is established, the telephone traffic for the macroscopic scenario covering Doha is abstracted using a mapping process described in the following subsection.

The distribution of cells of the cellular network in Doha, Qatar is taken from the publically available data on an actual MNO, i.e., Ooredoo.[1] In [43], a short overview of the qualitative LTE network coverage of the MNO Ooredoo is given. An LTE network was planned from scratch using the available information as an indicator of the density of the existing network. The parameters for the network planning process can be found in Table 2. According to actual network deployment in Qatar, a carrier frequency of 800 MHz with a system bandwidth of 10 MHz was chosen. The same antenna diagram for Kathrein 65° panel antenna type 80010306 [44] was used for all deployed antennas. Moreover, the transmit power of all antennas was set to 46 dBm for path loss prediction. All LTE resources in any network cell were utilized simultaneously to obtain a worst-case result for the network behavior. It results in a cell load of 100% and, therefore, a maximum possible inter-cell interference situation.

A basic intensity map was generated using the network-wide traffic requirement as input and distributed among the land-use classes of the whole scenario to evaluate the basic functionality and ensure a good network density.

As the paper focuses on vehicular users, the intensity map was generated for the morning rush hour, when most of the population is on the way to work. The first version for the LTE 800 MHz network design is shown in Fig. 3(a). Afterward, a path loss prediction simulation based on the well-known Okumura–Hata Macro prediction model [45] was performed for the entire scenario with a pixel granularity of 10 m × 10 m for a preliminary version. With the knowledge of the primary network configuration and assuming a worst-case interference situation, it is possible to generate maps for reference signal received power (RSRP), SINR, and cell assignment probabilities (CAP). The corresponding SINR map for a maximum cell load situation is shown in Fig. 3(b).

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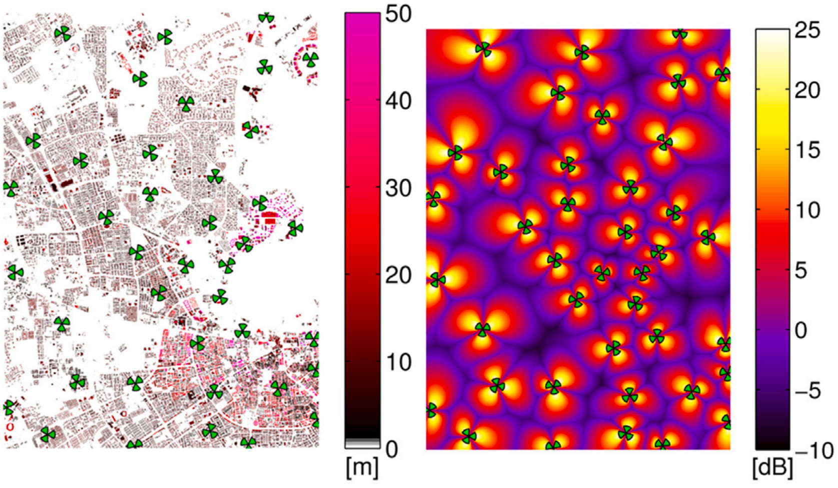
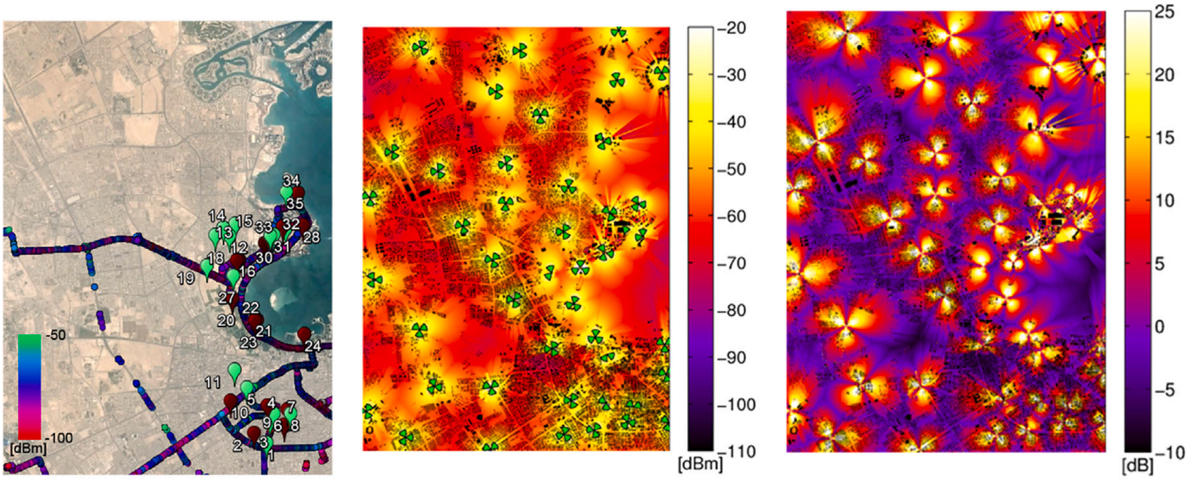
[1] Ooredoo - https://www.ooredoo.com/en/.



(a) (b)

Fig. 3. (a) LTE network antenna positions (preliminary version). (b) Full load SINR map for LTE network (preliminary version) with antenna positions.



(a) (b) (c)

Fig. 4. (a) Measured received signal power and base station locations identified throughout the driving test. Numbered markers represent base station locations, where red indicates probable Ooredoo base stations. (b) Ray Tracing result: Partial RSRP Map (final version). (c) SINR Map for worst-case interference situation.

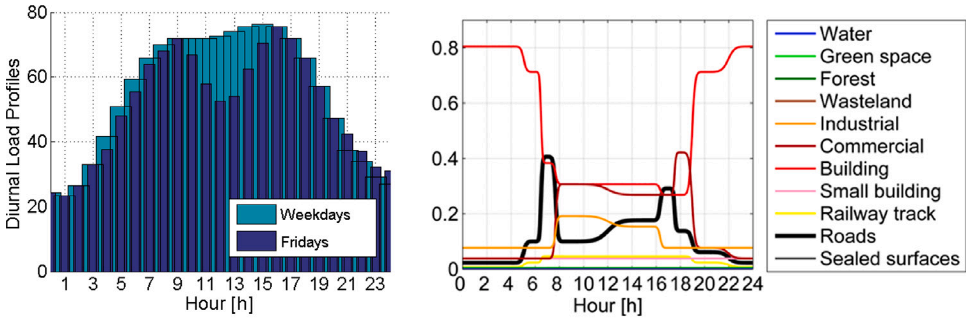
3.2.2. Network refinement through measurements

We conducted a measurement-based campaign to refine further the network and configuration resulting from the steps described in the previous subsection. For this purpose, a driving test was conducted. The received power levels and cell information of the Ooredoo global system for mobiles (GSM) and universal mobile telecommunications service (UMTS) network were logged. In addition, all visible antenna locations along the route were marked. The combination of the measured signal strength data with the marked locations is used to identify potential base station locations of the existing Ooredoo network. The typical procedure of rolling out a new network, i.e., LTE for Ooredoo, is to upgrade existing base stations and only build new sites if necessary. The areas for the driving test were chosen to provide scenarios for a wide range of use cases, later on, to be simulated. Thus, multiple intersections in a densely built-up area, namely the old airport area, and sections of the Corniche area, such as multi-lane roads with dense traffic or higher speeds, were traversed.

The results of the measurement campaign are shown in Fig. 4(a). On each measured position, each dot indicates the signal strength by a color given in the respective legend in the figure. Moreover, all visually identified antenna positions are marked on the map, where the red markers indicate Qatar's local MNO Ooredoo most certainly operates the base stations. On the other hand, the green markers are most likely base stations not operated by Ooredoo and, therefore, not considered for the refinement process of the virtual network in the reference scenario. A ray optical path loss model has been used to predict the respective outdoor cell coverage for the final version of the LTE network within the macroscopic scenario. The ray tracer outcome is depicted in Fig. 4(b), and SINR map is illustrated in Fig. 4(c).

3.2.3. Traffic intensity generation/daily user activity pattern

The time-variant data traffic offered to the network depends on users' whereabouts and the activity pattern, which changes significantly over one day. In [46], the authors analyze collected data from an extensive large-scale measurement campaign in a real network and present an emerging subscriber activity pattern over an extended period. The authors further use this set of data in [47], where a detailed simulation scenario for the city of Hannover, Germany, is presented. For the macroscopic scenario, this approach is revised where the distributions valid for typical user behavior are modified according



(a) (b)

Fig. 5. (a) Diurnal Load Profiles for Doha, Qatar, during weekdays, including Saturdays and weekends Fridays. (b) User distribution over different land-use classes for a working day.

to the typical situation in Qatar. Fig. 5(a) depicts the adapted discrete diurnal load profiles for Doha, Qatar.

For simulations and the generation of intensity maps, the analytical representation of the user activity distribution is discretized to one value for each hour of the day. The respective distribution for Qatar is modified by shifting the entire distribution one hour towards the early hours of the day. For Sundays, the same qualitative distribution as for weekdays is used. As a difference, the absolute values are downscaled according to lower expected absolute network subscriber activity. As for many Islamic countries, Fridays in Qatar are no working days, and usually, many people attend public prayers at noon. These local characteristics had to be considered a significant difference in the potential user activity within the network during the remaining days of the week. Hence, the diurnal load profile for weekdays is adapted accordingly by including a significant dip in the distribution around noontime to model the mentioned behavior. Moreover, the relative network subscriber activity in the early morning and later evening was subject to minor modifications.

3.2.4. *Spatial traffic distribution*

A detailed description of the traffic distribution process is given in [48]. This subsection gives an overview of the process and describes the deviations necessary to adapt it to the data available in the project.

In a cellular network, the base stations keep track of the amount of voice and data traffic they serve in aggregated counters for a given period, e.g., 15, 30, or 60 min. As these logged values, besides others, are indicators for network performance, they are called key performance indicators (KPIs). In spatial traffic distribution, the first step is determining the area where each cell is the best server. The cells reported traffic is then mapped to this area. The mapping inside that area considers the different land-use classes present and attributes a different fraction of the traffic to each land-use class depending on the time of the day. The mapping reflects the mobility of the users throughout the day. For example, whether they are on the roads while on their way to work or indoors at night. The weighting of each land-use class changes throughout the day to reflect the changing user locations. Fig. 5(b) shows the distribution for working days, taken from [48].

As the original process in [48] uses KPIs from each cell in a cellular network, which are not available for our simulated LTE network, we deviate from the process and distribute a total network KPI instead of cell-specific KPIs. Thus, a value for the total data traffic in the whole LTE network is used and distributed over the network's coverage area instead of cell-specific data over cell coverage areas. The original value of the network's total traffic intensity is normalized to be 1 and is then scaled according to the user activity patterns described in the previous section. The obtained traffic intensity maps can then be adapted to model different amounts of maximum network load throughout the peak usage, the so-called busy hour. The relative intensity fluctuation throughout the day, given by the user activity patterns, remains unchanged. Fig. 6 shows an exemplary result of the traffic generation process. An example of different spatial traffic situations for the morning rush hour (7:00–8:00) is given in Fig. 6(a). Fig. 6(b) shows spatial traffic distributions for the late evening (22:00–23:00). During rush hour, the traffic is concentrated in the streets, while most user activity comes from buildings and residential areas in the evening.

Since no MNO was part of the project, the simulation framework does not include actual network traffic data. However, in the future, the proposed framework can easily with augmented with actual network traffic data. Nevertheless, the network traffic, including the user distribution, their activity patterns, and, therefore, the traffic intensity map, are estimated based on the modified models according to the land-class usage and daily situation in Doha, Qatar.

3.3. *Developing the microscopic-layer*

The investigation of LTE C-V2X communication requires a well-defined set of microscopic scenarios. These scenarios will allow emulating of realistic traffic situations, including vehicular mobility and user behavior, and demonstrate the communication performance for specific use cases and applications through computer simulations. Within the context of this paper, both road traffic and data traffic conditions are covered to investigate the load and interference analysis of incorporated communication technologies.

3.3.1. *Creating vehicles and generating mobility traces*

The vehicular movement traces were generated using the SUMO traffic simulator to include vehicles within the simulation scenario. The processing pipeline of microscopic-level vehicular mobility traces is divided into three steps.

- Map download and conversion: The road network layout of the entire simulation region is downloaded from the OpenStreetMap (OSM) [49] – a repository of freely available geographic data. The extracted data in OSM file format is then converted into SUMO-compatible XML format using the netconvert utility software. The raw data with several inconsistencies and inaccuracies goes through a series of networking editing, e.g., the number of lanes and geometry adjustments to remove errors in the road network. It includes manual and automatic post-processing and rebuilding of the entire scenario.
- Traffic generation: While there can be three components, namely cars, public transport, and pedestrians, in any example traffic scenario, the reference scenarios only included cars. In traffic scenarios, the cars use the fastest route between the randomly selected origins and destinations. Towards this end, a list of permissible random road trips was generated. Finally, the trips

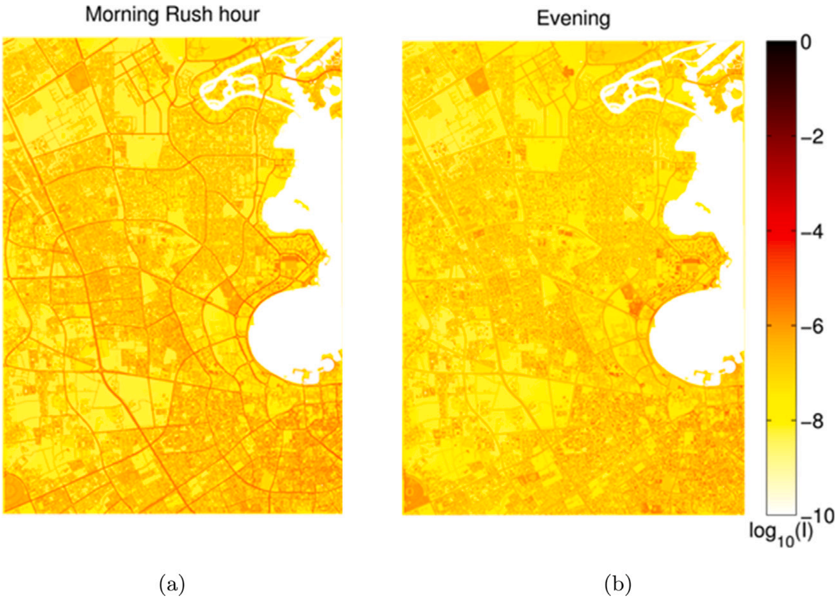
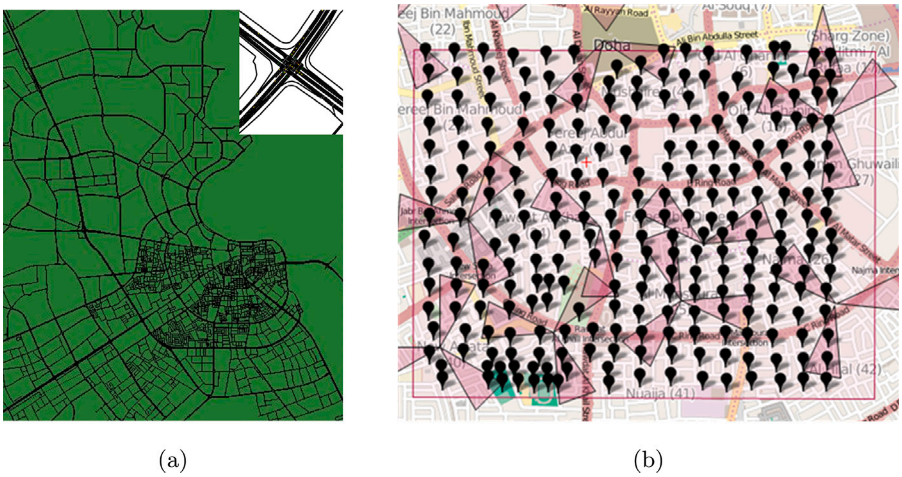


Fig. 6. Traffic intensity maps for different times of the day (a) Morning rush hours and (b) Evening.


(a)

(b)

Fig. 7. (a) Road layout obtained from OpenStreetMap (OSM) and illustrated in SUMO-GUI. The inset shows vehicles near an intersection. (b) The 512 background users represent the scenario's downlink and uplink traffic.

are converted to routes by computing the shortest or optimal paths to the traffic flow. Only plausible trips are shortlisted to achieve the traffic-filled network.

- Mobility trace extraction: In the final step, the movement patterns for each vehicle are generated by combining the road geometry, trip, and route data in the FCD format. The FCD format includes the vehicle's current location, velocity, and angle information. The movement patterns must be translated into microscopic-level vehicular mobility traces using the TraceExporter utility tool to use FCD formatted data with system-level simulators like ns-3 and SiMoNe. Fig. 7(a) shows the road layout illustrated in SUMO-GUI.

3.3.2. *Modeling cellular network traffics*

For a realistic network load study, LTE users are needed to create downlink and uplink traffic. The cell load, as the number of totally used physical resource blocks related to the available number of resource blocks, depends on three main factors:

- The number of users causing uplink or downlink traffic.
- The amount of traffic caused by each user depends on the type of traffic, such as voice calls, web browsing, gaming, or video streaming.
- The SINR determines the number of physical resource blocks needed for a user to handle the traffic demand.

The number of users can be estimated by processing a traffic intensity map. This map reflects the probability for every location to hold a user. The map can be scaled with a constant traffic demand factor to hold the macroscopic traffic demand for every pixel. The downlink interference is caused by the base station, fixed to a static position. Therefore, the interference for every pixel can be calculated by using the path loss from every base station to every pixel. The power of the serving cell is then put into relation to the network load of the surrounding cells as the source of interference.

The amount of interference highly depends on the positions of the radiating source. The macroscopic model described above cannot be used for uplink investigations since the source of interference strictly depends on the user positions. Using every pixel of 10 m × 10 m as a user would lead to 120,000 users and overcharging the complexity that the simulator can handle. The intensity map was thus used to create users, representing the traffic demand for a region with multiple pixels to model the uplink traffic. For the creation of users, a tessellation algorithm [50] was used. The traffic intensity map is split into slices holding an equal amount of traffic demand. With this algorithm, 512 users were created, each representing 0.195% of the overall traffic demand in the given scenario. The traffic centroid for every slice was used as the user position. This approach leads users to a constant bit rate (CBR) request. As a result, areas with dense traffic requests are represented by multiple users, while areas with low traffic requests yield fewer users. The distribution of the 512 users is shown in Fig. 7(b) for the subregion of 4 km × 3 km of the simulated scenario.

The amount of downlink CBR traffic requests for every user is equal to the sum up of the slice within the scaled-up traffic intensity map. For the correct upscaling, it is assumed that the mobile LTE network was planned so that the mean downlink network load would not exceed 80% in the busiest hour. The scaling allows the most loaded cell in the scenario to have a load of nearly 80% in the downlink. Furthermore, the uplink traffic is assumed to be 1/6 of the downlink traffic [51]. With this approach, the downlink CBR of every user results in 520 byte/s with an uplink traffic demand of 87 byte/s.

4. System-level simulator for LTE C-V2X communications

In a mobile cellular network, wireless communication occurs in two directions, the direction from the base station to the subscribers, called the downlink, and from the subscriber back to the base station, the uplink direction. Due to the differing interference mechanism, the simulation of downlink and uplink are structured differently. While the interference in the downlink occurs at the mobile receiver and is caused by neighboring cells, the uplink interference occurs at the base station's receiver. It is caused by mobile users being scheduled in the same resource blocks. So no users within one cell will be assigned the same resource. In the downlink case, the interferers have a fixed position. The interference at the mobile receiver depends on the cell load, transmission power, and the pathloss between transmitter and receiver.

For the uplink case, the position and transmit power of the interferers depend on the uplink scheduling decisions of the network. Therefore, consideration of scheduling and power control is crucial for uplink simulations. The details of the interference and SINR computations for the downlink and the details of the chosen modeling approach for uplink simulations are described in the following subsections.

4.1. Downlink simulation

Fig. 13 depicts the SINR and load calculation schematic process in SiMoNe.

Depending on the used type of user demand, the distinct users, in the case of microscopic simulations or the pixels of the traffic intensity map, are considered user demand. For each user demand, the position and the respective pathloss to the base stations in the scenario are available from the database. Based on the pathloss predictions, the reference signal received power (RSRP) in the downlink at each position of the scenario is determined, and the actual network simulation for the downlink starts. With this information, an iterative process is started to compute the respective SINR and the resulting cell loads. At the beginning of the iteration, the cell loads are not set and are initialized with arbitrary values.

The interference caused by the neighboring cells is calculated under the assumption of a linear, uniform power spectral density in the whole carrier using the set cell load values. For example, using the following equation, a cell with a nominal transmission power of 46 dBm, loaded 50%, interferes with a power of 43 dBm.

$$46\text{ dBm} + 10.\log(0.5) = 43\text{ dBm} \qquad (1)$$

The SINR for each user demand is computed with the interference and the pathloss to the serving cell. The required number of resource blocks for each user demand is determined for all user demands of a cell, using abstractions from link-level simulations, resulting in an initial cell load. The underlying scheduling is assumed to be following a proportional fair approach. Thus, all users are assigned their requested resources. The required resources surpass 100% if the cell overloads and all user demands are throttled equally. It is done for each cell in the network. Afterward, the load values of the cells are compared to the starting values. If the difference for each cell load is below a given threshold *MaxDiff*, the network state is considered stable, and the iteration ends. Otherwise, the cell loads are updated with the preliminary values, and the SINR and cell loads are determined again.

Subsequently, the KPIs of interest is determined, the simulation time is changed to the next step, and the user demands and pathloss values are updated before the iterative load calculation starts anew. Cell-centric metrics like load, throughput, amount of served users, and the probability of blocking can be deduced using this mechanism. Performing further analyses on the SINR and RSRP, user-centric metrics like handovers and radio link failures can be obtained in addition to load-related KPIs like throughput.

4.2. Uplink simulation

This section describes an uplink simulation's general flow and the modeling assumptions.

Compared to the downlink simulation, the uplink simulation requires more detailed knowledge about the actual resource allocation as the uplink interference in one resource block at the base station strongly depends on the position and transmit power of the different users transmitting on the same resource block. Thus the user demand is processed in the format used for microscopic simulations. If traffic intensity maps are incorporated for uplink computation, a representation of microscopic user demand must be used. The modeling approach presented in [52] is employed to reduce the complexity and runtime of an uplink simulation. The main steps of a simulation cycle are illustrated schematically in Fig. 14 and are elaborated in the remainder of this subsection.

The exact pathloss predictions, from base stations to positions in the scenario, as in the downlink, can be used for the uplink case. With the user position, the pathloss between each user, the scenario base stations, and the user demand, the subroutine to calculate the SINR and load is started.

In the uplink, the maximum amount of resources, i.e., physical resource blocks (PRBs) a UE can concurrently transmit, depends on many factors. It includes maximum allowed transmission power, the pathloss between user equipment (UE), serving base station antenna, and the power control parameters set by the network. Thus, in this step, the transmission power per PRB and the maximum supported amount of PRBs per UE is determined to be used in the subsequent scheduling abstraction.

The number of resources assigned to each user is determined based on the maximum amount of supported PRBs and the chosen scheduling approach. Currently supported scheduling approaches are Strict Resource Fair, Modified Strict resource Fair, which avoids empty bandwidth due to power-constrained users, and Throughput Fair, and QoS, which assigns resources based upon the actual user demand. In the case of the QoS scheduling approach, the amount of assigned resources depends on the uplink SINR of each user. If available, a value from the previous simulation is used as the initial assumed SINR. If there is no data from the prior simulation, the SINR is estimated based on the pathloss and a configurable default SINR value of the cell user with the worst SINR, which is assumed to be 0 dB. Once the assigned amount of resources is known, the probability for each user to be assigned one PRB is determined. For example, assuming a strict resource fair scheduling approach and 5 users in a 10 MHz LTE cell that offers 50 PRBs, each

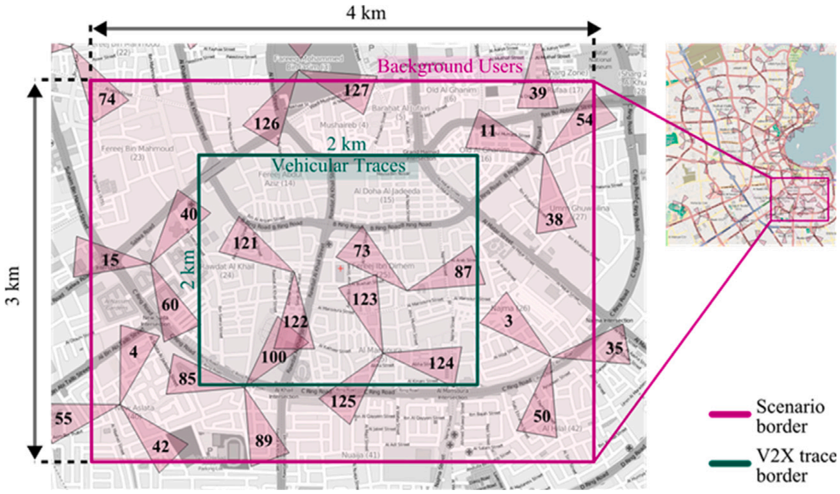


Fig. 8. The simulation scenario for C-V2X communication over LTE network.

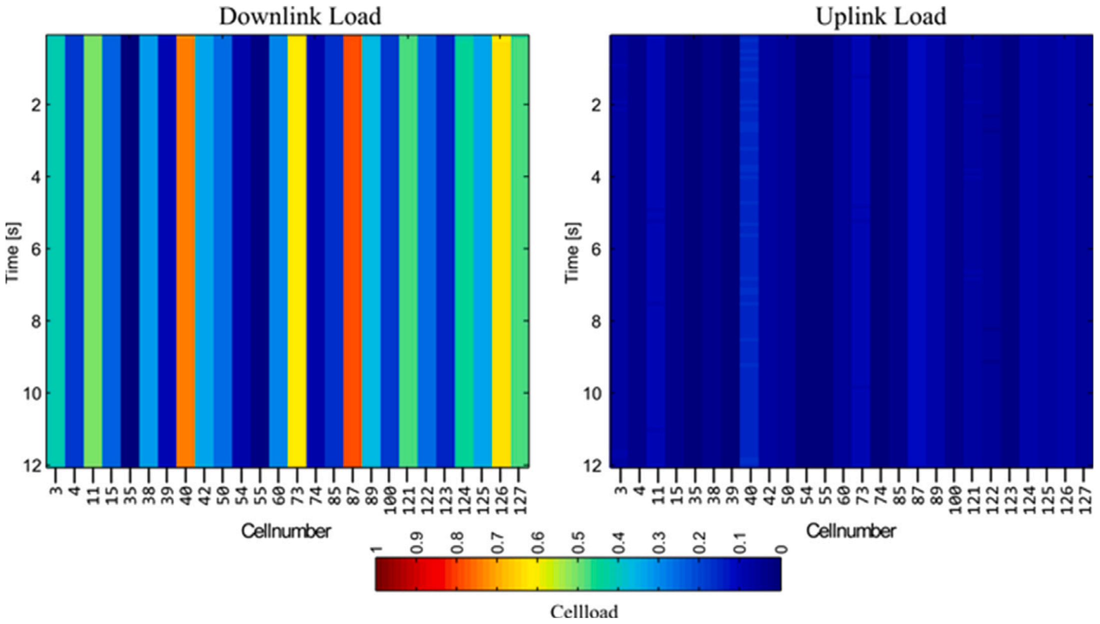


Fig. 9. Downlink and Uplink load for the scenario (only background users).

user would be assigned 10 PRBs. Thus the scheduling probability p_s for a user, u would be $p_{s,u} = 0.2$.

The computed scheduling probabilities are then used for a scheduling abstraction using a Monte Carlo approach. For this purpose, two aspects must be considered. Firstly, 2000 realizations of resource assignments for all cells are generated based upon the scheduling probabilities of each user in each cell. Secondly, the average resulting uplink interference at each cell is determined. The authors of [52] state that 1000 iterations are sufficient to achieve stable values, but due to the larger scenario size, we increase the number of iterations by a factor of two.

The average uplink SINR for each subscriber can be determined using the average uplink interference at the base station. In the case of the QoS scheduling approach, the number of required resources and scheduling probabilities is updated after the initial SINR estimation, and the scheduling abstraction is computed anew to obtain updated average uplink SINR values. Once the average uplink SINR for each user is known, cell- or user-centric metrics, e.g., cell load, throughput, or blocking-related information, can be derived. If the KPIs of interest is derived, the simulation time is increased, and the user demand and pathloss values are updated before the following SINR/Load computation procedure is started.

The proposed framework includes Simulator for Mobile Networks (SiMoNe), a link-level and system-level simulation platform for V2X communications. Although this article focuses on V2N and V2N2V communications based on the Uu interface, the framework can simulate direct communications such as V2V, V2I, and V2P using multiple radio access technologies or multi-RATs support simultaneously. More precisely, the framework not only provisions LTE-V-Cell (Centralized mode) [53] utilizing the base station (eNodeB) as the central ITS server and data forwarding entity but also includes support for LTE-V-Direct (Decentralized mode). The proposed framework can be applied to implement, test, and evaluate advanced V2X applications such as remote driving for remote control of vehicles, vehicle platooning, etc.

SiMoNe maintains a repository of transmission technologies, frequency bands, mobility traces, and cell positions and extends it by interfacing with other simulators. SiMoNe is constantly being extended with new features such as self-organized networks (SON) [54], communication between drones and mobile radio cells, Terahertz communications [55], and channel models for the simulation of different

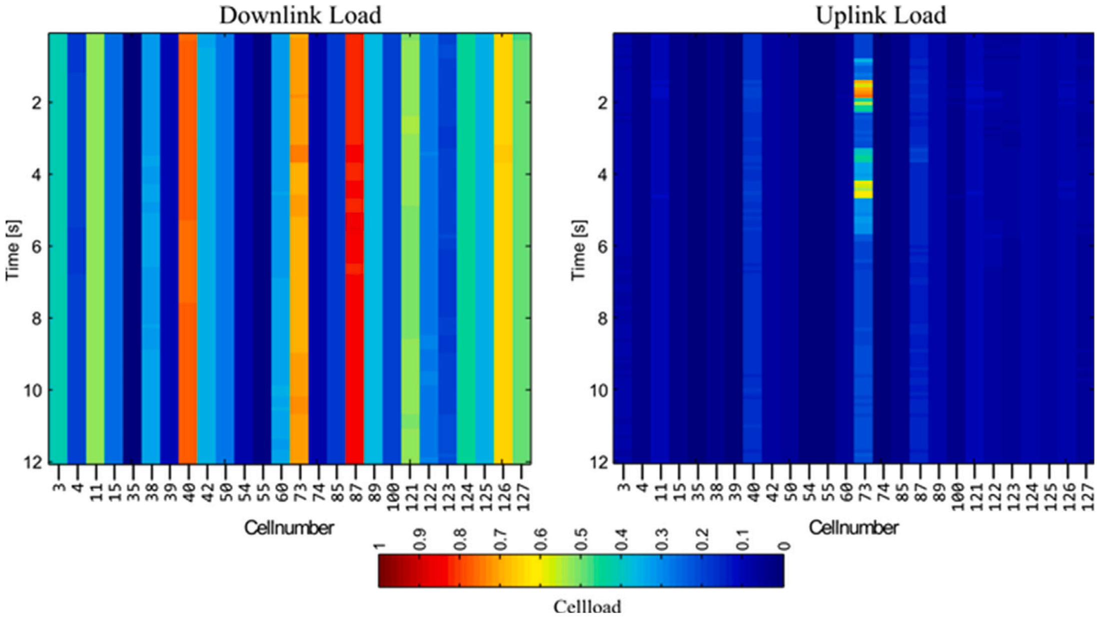


Fig. 10. Downlink and Uplink load for the scenario with background and vehicular users.

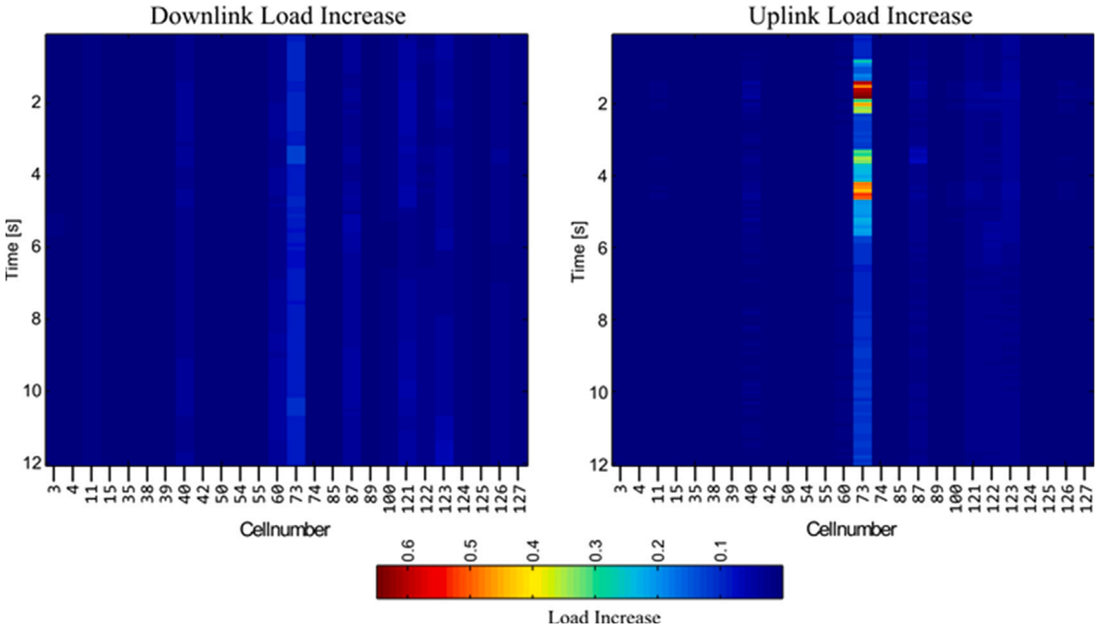


Fig. 11. The increase of downlink and uplink load when adding vehicle users to the simulation.

RATs [56]. The modular composition of the SiMoNe simulator allows the new functionalities to be bundled in interchangeable and connectable modules. More recently, SiMoNe has been extended with support for sidelink technologies such as IEEE 802.11p, LTE-V-Direct (Decentralized mode), and both mode 3 and mode 4. In [57], SiMoNe implements ray tracing and stochastic channel models such as WINNER+ [58] to evaluate different sidelink technologies. For Mode 3, the eNodeB randomly assigns available resources to a sorted/prioritized list of subscribers, whereas the resource management in LTE-V mode 4 utilizes Sensing-Based Semi-Persistent Scheduling (SBSPS).

There are proposals to share the 5.9 GHz ITS band between IEEE 802.11p based (DSRC) and LTE-V-Direct [59]. In [59], the authors proposed a dual-interface enabled scheme in which both IEEE 802.11p (DSRC) and C-V2X are allocated a specific wireless channel with a guard band. With multi-RAT support, vehicles were able to communicate over both interfaces simultaneously. In our earlier work [13], we implemented a dual-interface enabled hybrid vehicular communication system within SiMoNe, consisting of IEEE 802.11p and 4G/LTE interfaces. Our previous work can be further extended in this direction to support LTE-V-Direct support over the PC5 interface sharing radio resources with DSRC enabled network while maintaining the V2N/V2N2V link over the Uu interface.

5. Simulation results

Since many users use LTE, it has to be considered how many vehicles of a V2X communication system can be supported next to competitive users, sharing the same radio resources. The investigations were done with the SiMoNe. First, a scenario was created based on worst-case assumptions to approximate the number and locations of competitive LTE users. In the second step, V2X users were added to the

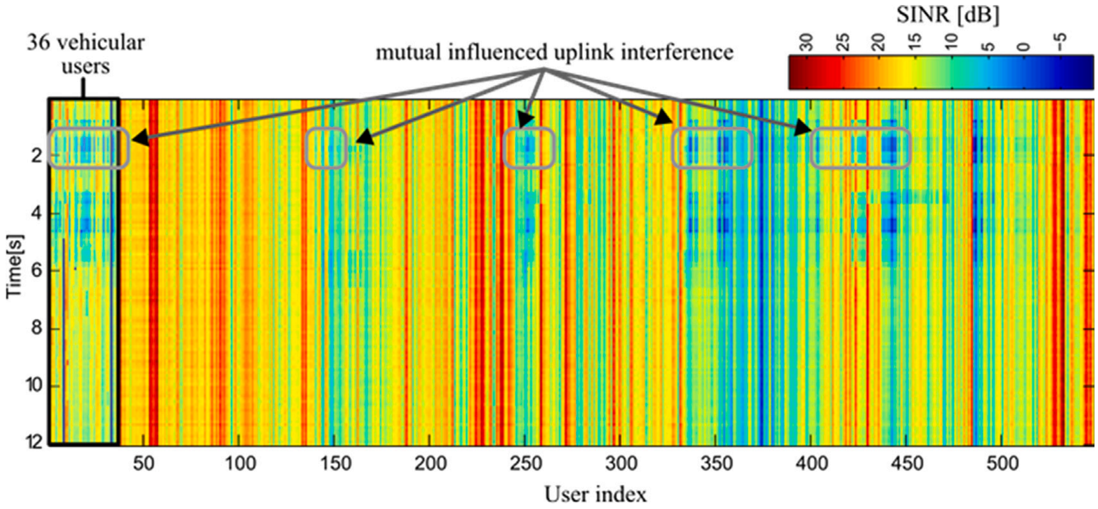


Fig. 12. The uplink SINR in the scenario for the 36 vehicular and 512 background users.

simulation scenario to analyze the load increase for the downlink and the uplink. The simulation results consider land-use classes and user demand while calculating SINR and network load.

5.1. Scenario description

The scenario for this study is located in the Old-Airport area in Doha, Qatar. The scenario has a size of 12 km^2 (4 km × 3 km), including 26 LTE cells. All simulations are done for a resolution of 10 m × 10 m (called 'pixel'). Fig. 8 shows a map with the scenario marked with purple borders.

The interference must be guaranteed in every location to create a realistic uplink and downlink interference for the V2X traces. Therefore, the traces must be located inside the scenario with a margin to the scenario borders. The minimum margin was set to 500 m and is marked with green borders in Fig. 8. Nevertheless, all traces are located near the scenario center. The CBR of a V2X user is set to 4.9 kByte/s for the uplink and downlink directions. The message size is 500 Bytes with a sending frequency of 10 Hz. This traffic pattern represents the worst for sending cooperative awareness messages (CAM) in the maximum allowed sending frequency.

5.2. Load and interference analysis

The simulation results presented focus on load and interference analysis. The scenario was first analyzed without using V2X traces to investigate the load and used bandwidth of the competitive LTE users (background users) for all cells in the scenario. Fig. 9 shows the downlink and uplink load for all cells.

Because the background user is static and does have a constant traffic demand, the load is also constant in time. The downlink load for the cells, numbered in Fig. 9, ranges from zero (cell 35 and cell 55) to the maximum load of 0.795 (cell 87). The load for the cells differ in such an extensive range between 0 and 0.795 since the background user are not equally distributed, based on the traffic intensity map. Especially cells 35 and 55 are located at the scenario edges and do not serve any of the background users. The most loaded cells, 87 and 40, serve a more significant area than others, thus serving the most user demand. For the uplink, the maximum load is reached again for cell numbers 40 and 87, carrying a load of 0.16. The uplink load, in general, is low compared to the downlink since only a fraction of the downlink traffic is demanded by the uplink.

As vehicular users, 36 traces are used while requesting a constant bit rate for the uplink and downlink. It has to be noted that in contrast to the background users, the vehicular user traffic is symmetric with the same bit rate for uplink and downlink. This approach is based on the feature in LTE Rel. 8 allowing a broadcast delivery of messages. Thus one CAM message of one vehicle in uplink will cause again one broadcasted CAM message for all other vehicles in downlink resulting in symmetric uplink and downlink traffic. The 36 traces, each requesting 4.9 kByte/s, were scaled up to represent more than one vehicle. The network's uplink changes into an overload state for a vehicular scaling factor of 5. Therefore, a scaling factor of 4 is taken as the maximum number for the scenario to handle all vehicular traces. The uplink and downlink load are shown in Fig. 10. Beyond that, Fig. 11 shows the load increase for up and downlinks after adding the vehicular users to the scenario.

It can be noted that the traffic increase for the downlink is slight and almost constant. The maximum load increase is 0.12 for cell 73 at 3.4 s. Cell 87 holds the maximum load of 0.84 again at 6 s. On the other hand, the uplink traffic highly depends on the time. The load in Cell 73 varies from 0.19 up to 0.75 at the time of 1.8 s. The load variation is caused once through the position, depending increase of interference between the moving vehicular users and the static background users, and second through the position-dependent path loss between the vehicular users and the base station. If the uplink condition for a vehicular user is poor, the traffic demand can highly increase.

The most important and complex factor for the cell load is the SINR, shown in Fig. 12. Fig. 12 shows that the SINR of the users is coupled. If one user suffers from a path loss increase, the user must allocate more resources to serve the throughput demand. As a result, all other users in the surrounding cells will suffer from increased interference, resulting in a higher demand for physical resource blocks. The disturbance of interference for the vehicular users leads to an SINR degradation of the static users. A deeper analysis of critical cell 73 has shown that for the time of simulation, 32 background users and 17 vehicular users (representing 68 cars) are connected with cell number 73. It is assumed that all 68 cars transmit the maximum number of CAM messages in the most loaded hour of the day over the LTE network, resulting in the maximum load of 75% in uplink and 84% in the downlink. From this point of view, the results strengthen the perception of using LTE as a centralized network for V2X communication.

6. Conclusion

This paper proposed a top–down approach for building realistic reference scenarios. It also includes the development of a simulation framework, which integrates traffic, network, and radio channel simulator for realistic system-level evaluation of LTE technologies. For this purpose, algorithms and software module enhancements are made in

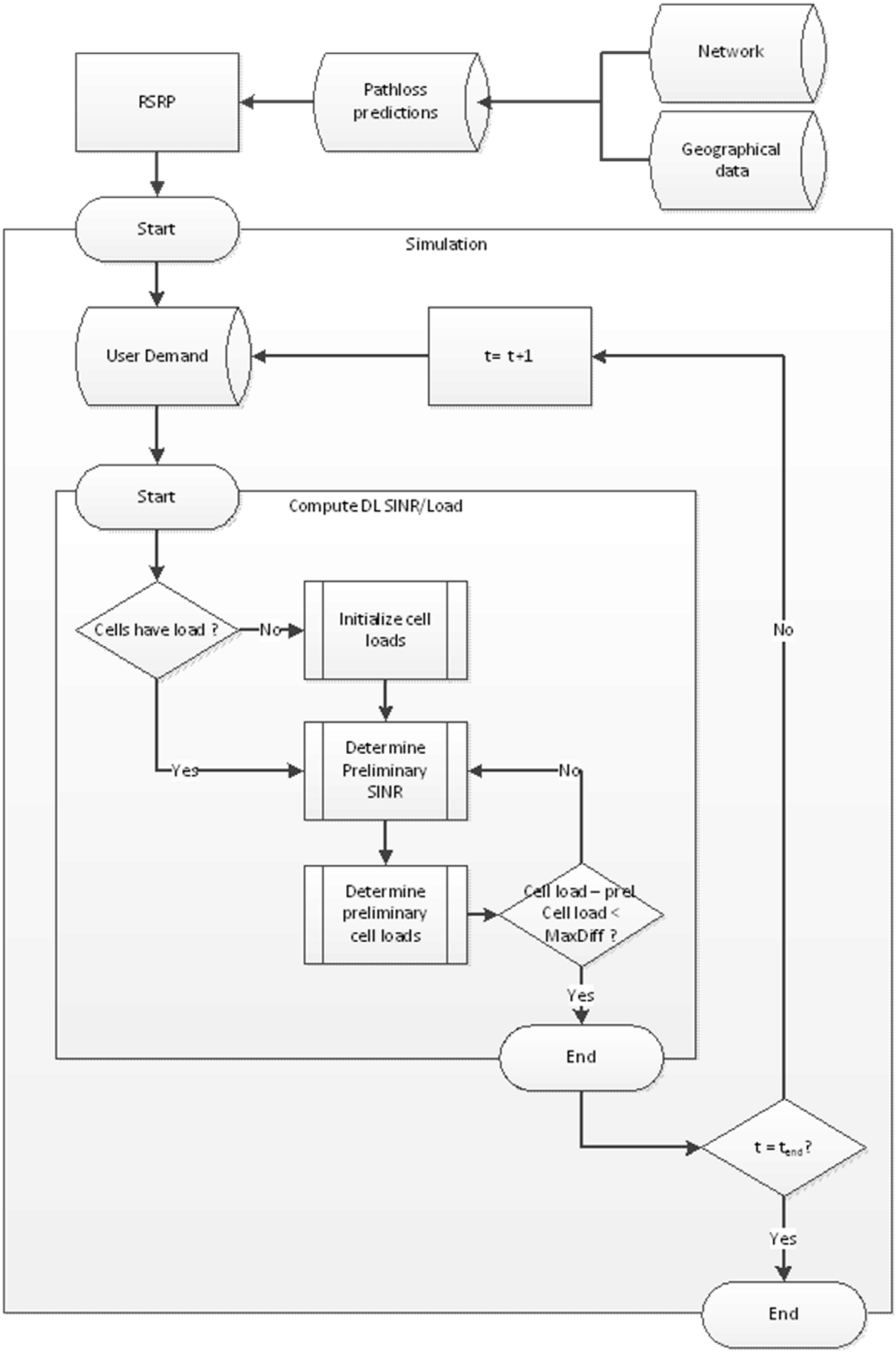


Fig. 13. Schematic downlink system-level SINR/load computation.

various simulators. The reference scenarios are set in the selected urban areas in Doha, Qatar. The first set of simulation results investigates the impact of background traffic on uplink and downlink load without V2X traffic. The static users generate constant traffic in the downlink, which does not vary in time. At the same time, the cell load varies because users are not distributed equally. Since only a fragment of downlink traffic is demanded for the uplink, the uplink load is low compared to the downlink. Next, the V2X traffic is introduced in the simulation, which shares radio resources with the background traffic. It is observed that the vehicular traffic is symmetric, and the cell load increases for the uplink while it remains almost constant for the downlink. The SINR of all users in the scenario is tied together, i.e., an increase in interference for V2X users results in SINR degradation of the static users.

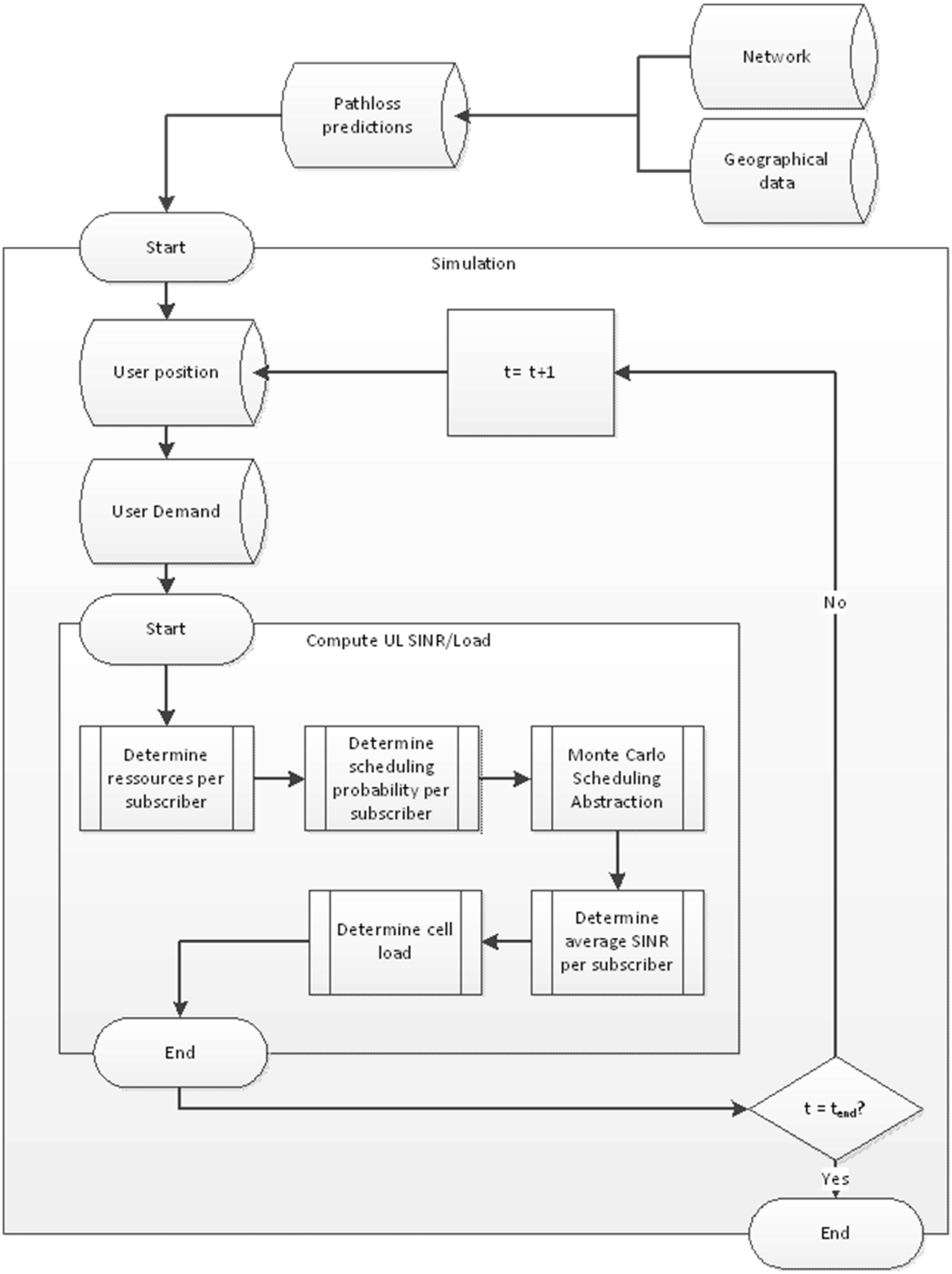


Fig. 14. Schematic uplink system-level SINR/load computation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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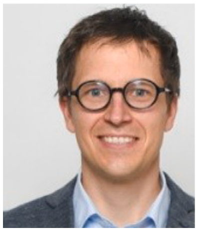

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