Simulation of Next-generation Cellular Networks with ns-3: Open Challenges and New Directions

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ABSTRACT

One of the main strengths of Network Simulator 3 (ns-3) is the availability of modules to simulate cellular networks, including LTE and mmWave/NR deployments. These implementations model the protocol stack with a high level of detail, and, thanks to the integration with the whole ns-3 code base, make it possible to study end-to-end scenarios and identify complex interactions between the different components of a network. In this white paper we discuss the current limitations of this platform, and suggest directions for future work that could improve the accuracy of the simulations.

CCS CONCEPTS

• **Networks** → **Network simulations**; **Mobile networks**;

KEYWORDS

ns-3, cellular networks, mmWave, scenarios, mobility models

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1 INTRODUCTION

Network simulators are fundamental tools to assess the effectiveness of novel designs, architectures, and algorithms for networking problems, offering the possibility to monitor the performance of the overall system in a controlled environment, with different scenarios and parameter settings, and without the need for a real deployment. Among the many simulation tools that have been developed so far, either commercial or open source, Network Simulator 3 (ns-3) stands out for its modularity, flexibility, and realism. Indeed, ns-3 provides several simulation modules which can be easily interfaced together and extended in order to simulate even complex and realistic cellular deployments and to account for all the phenomena influencing the network behavior using the desired level of abstraction.

In order to provide a solid support for the research in this field, simulation tools should be updated in parallel with the evolution of the cellular technology, either by enhancing the existing models or by adding new ones. In this regard, ns-3 is being enriched to provide support for the simulation of the latest cellular (i.e., 3GPP NR [1]) and Wi-Fi technologies (i.e., IEEE 802.11ax [10] and 802.11ad/ay [9, 11]).

In this paper, we discuss the current limitations for the simulation of cellular networks with ns-3 and provide some future directions to fill the gaps. In particular, in Section 2 we give a general description of the simulation of cellular networks, outlining the simulation models which account for the main phenomena influencing the system behavior. In Section 3, we discuss the limitations of the models currently included in the ns-3 framework, and give our point of view on how to overcome the open issues. Finally, in Section 4 we draw some conclusions.

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2 SIMULATION OF CELLULAR NETWORKS

The evaluation of cellular systems typically involves three different methodologies, which have different purposes and are usually exploited jointly in order to fully understand the system behavior, namely analytical modeling, real-world measurements, and simulation. In particular, analytical modeling provides a general characterization of the system and a preliminary evaluation, usually through the derivation of bounds and/or approximations for the system performance. However, it may be difficult to devise mathematical models capable of capturing all the relevant dynamics, and several assumptions may be needed to make these models tractable. On the other hand, measurement campaigns on prototypes or real systems could provide very accurate results, but they are very expensive and difficult to conduct. Sometimes the realization of a working prototype may not even be feasible, because the required hardware may not be available on the market. Finally, simulations consist in mimicking the system operations by means of one or multiple models describing the system and the phenomena influencing its behavior, with a certain level of abstraction. The latter is chosen according to the desired evaluation accuracy, allowing the testing of the system performance at different scales and in different situations. Also, simulations make it possible to arbitrarily set the operating conditions under which the system has to be tested, and to reproduce them at any time. Therefore, simulation allows the comparison of the performance of different variants of the system or different configuration options and is consequently an important tool in network architecture and protocol design.

Nonetheless, the reliability of the evaluation results mainly depends on the quality of the simulation models, which have to be detailed enough to include the characterization of all the phenomena of interest, and this may be challenging when the system is too complex.

A cellular network is an example of an extremely complex system, as shown in Figure 1, in which different elements impact the overall performance in different ways and at different scales. For

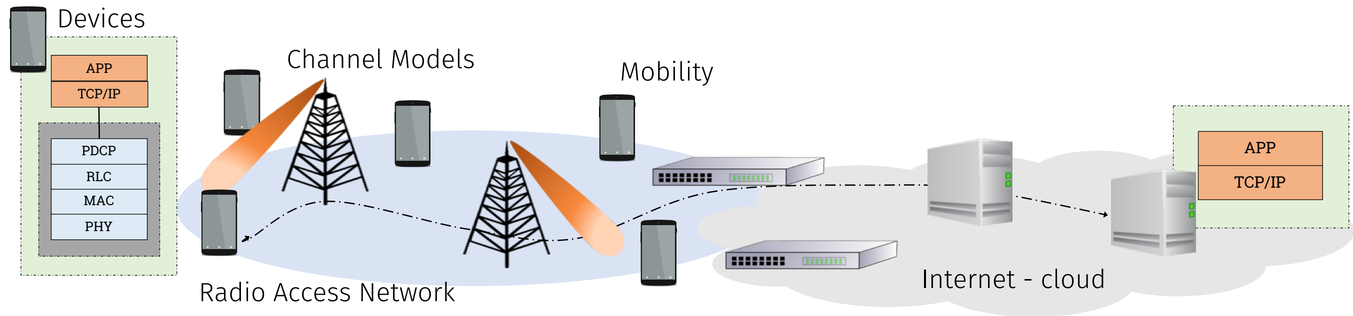

Figure 1: Elements Involved in the End-to-end Simulation of a Cellular Network

instance, user mobility, data traffic, and the propagation environment may dramatically change the network behavior, thus their characterization is of fundamental importance to obtain a proper level of accuracy [6]. To this aim, network simulators, such as ns-3, typically provide multiple simulation modules, each focusing on the modeling of a different phenomenon, which can be interfaced together to obtain a thorough description of the overall system. Also, each module may provide multiple models describing the same phenomenon in different ways, e.g., at different levels of abstraction or using different approaches.

In general, the simulation of cellular networks involves both the modules implementing the cellular technology of interest, which provides a model of the Radio Access Network (RAN) and the core network, and other modules which take into account the external phenomena influencing the system behavior. While the realization of RAN and core network models is straightforward, because they are completely defined by the cellular standard, the design of models to account for the external phenomena is more problematic because of their stochastic nature, as we discuss in the following.

2.1 Channel Model

The channel model describes the propagation of the signal through the surrounding environment, taking into account different factors influencing this phenomenon, such as the carrier frequency, the spatial characteristics of the channel, the presence of blocking objects. Given that the performance of cellular networks strongly depends on the nature of the wireless channel, proper modeling of its behavior is of primary importance to obtain accurate simulation results. This is particularly true for millimeter wave (mmWave) systems, in which the high carrier frequency and the directionality of the communications make the propagation of the signals very sensitive to the characteristics of the environment. Indeed, the presence of buildings, trees, or even the rain may reflect, attenuate and refract the signals, hence their influence has to be taken into account for proper modeling of the channel [4].

2.2 Application Model

The application model is used to mimic the generation of the user traffic. This is a very important aspect in the simulation, because it determines the load under which the network has to operate. The usage of inappropriate and unrealistic traffic models may lead to evaluating the system under conditions that are not representative of those encountered in real-world scenarios, thus potentially leading to wrong conclusions. Moreover, with the emergence of new applications (e.g., virtual and augmented reality, self-driving cars, tactile Internet), cellular networks have to deal with several types of traffic with very diverse characteristics, therefore a proper modeling of the behavior of the upper layers of the protocol stack is fundamental to obtain accurate results from the simulations.

2.3 Mobility Model

The mobility model characterizes the movements of mobile users in the 3D space. When simulating large networks composed of multiple cells or, in general, when the user mobility is significant, the usage of proper mobility models is an important aspect to consider in order to obtain accurate results. Indeed, user mobility has a strong impact on the cellular system, not only for the more problematic propagation of the signals due to the Doppler effect, but also for the frequent handover events which occur when a user has to change its serving cell. When considering mmWave communications, this aspect is critical [14], because even small changes of the positions of the users may radically impact the propagation conditions.

2.4 Support in ns-3

ns-3 provides different simulation modules, including multiple implementations of the aforementioned models. In particular, the `spectrum` and the `propagation` modules deal with the modeling of the wireless channel, the `application` module provides several traffic generation models, while the `mobility` module is used to account for the user mobility. Additionally, ns-3 includes other modules which can improve the realism of simulations, e.g., by modeling the presence of buildings and obstacles in the scenario. While the usage of these modules is a first important step for realistic simulation scenarios, their modeling capabilities could be improved to account for a number of factors that are important in next-generation networks. In the following section, we will outline the limitation of these models, and propose some enhancements to further improve the support for the simulation of cellular systems.

3 OPEN CHALLENGES AND NEW DIRECTIONS

In this section we will identify a number of open challenges that we faced while running extensive simulation campaigns, mainly related to mmWave cellular networks [12]. Then, we will suggest possible directions that can improve the suitability of ns-3 for the simulation of cellular networks in different scenarios.

Channel Models: next-generation cellular technologies will rely on communications at very high frequencies, e.g., mmWave [16] and Terahertz [8] communications, at which the signal propagation is strongly dependent on the spatial characteristics of the surrounding environment. Moreover, antenna arrays will be used to overcome the high attenuation experienced at such high frequencies by increasing the directionality of the propagation [16]. In this context, channel models currently implemented in ns-3 (e.g., Friis, Okumura Hata, trace-based fading model) do not take into account the necessary characteristics needed to properly model multi-antenna systems at these higher frequencies. To solve this problem, either *ray tracing*-based simulation or Spatial Channel Models (SCMs) should be used. While *ray tracing* yields the most realistic results, it is complex to program and debug as well as very computationally demanding to execute. Furthermore, it has to be specific for a given scenario, defining the geometry of the environment, materials of walls and obstacles, positions of receiver and transmitter. A more lightweight albeit less precise solution can be found in SCMs. These are stochastic channel models that consider multiple rays coming from different angles with different powers and delays, thus being able to model complex wideband channels. The ns-3 `spectrum` module has been introduced to model the propagation of the irradiated power through the wireless channel, but it currently lacks support for SCMs, and should be therefore extended. Although SCMs are still much faster than ray tracers, channels like 3GPP 38.901 [2] can act as bottlenecks given the large number of parameters and computations, especially when large arrays are considered. This is exacerbated by the fact that the code is rarely optimized.

Antennas: to overcome the high attenuation experienced at very high frequencies, next-generation cellular networks will use multi-antenna systems capable of directing the transmit power in the desired direction through suitable beamforming. The ns-3 `antenna` module provides single-element antenna models with isotropic, parabolic and cosine radiation patterns, but lacks a general model for antenna arrays which is essential for the simulation of next-generation cellular networks [18]. A possibility is to include the antenna array model provided by the `mmwave` module, which has been recently extended to support the radiation pattern specified in 3GPP TR 38.901 [17]. However, the current implementation cannot easily include new radiation patterns and does not support custom antenna orientation, and therefore it should be better generalized and extended. Especially for mobile users, in fact, having a vertical orientation is rather unlikely, while allowing an arbitrary rotation would make simulations more realistic.

Applications: while the need for accurate application models holds for the simulation of any kind of network, in mobile scenarios the user generally uses different interaction patterns than in wired networks. For example, bulk transfers of data are generally uncommon, while video streaming, web browsing, chatting and VoIP are more popular. In this regard, while ns-3 generally offers a number of statistical packet sources, it lacks implementations of applications that model complex interactions and expose Quality of Experience (QoE) metrics. There have been a few attempts aimed at simulating video streaming, through either the parsing of traces or the implementation of dynamic adaptive streaming over HTTP, however none of them has been integrated in ns-3 [3, 13]. In this domain, metrics such as the Structural Similarity Index (SSIM) or the Peak Signal to Noise Ratio (PSNR) are fundamental for the evaluation of the video transmission over the network. Moreover, other interesting source/sink models with interactions between the two endpoints of the connection include voice and texting. More futuristic applications that could be of interest for the evaluation of next-generation networks include virtual reality streaming, autonomous driving, mission critical services, and so on.

Buildings and obstacles: buildings and obstacles can severely impact the quality of mobile communications. ns-3 features a module that implements building in the scenarios, and is used by different propagation models (e.g., `HybridBuildingsPropagationLossModel` for LTE) to tune the propagation condition to the presence of a Non Line of Sight (NLoS) condition or an urban canyon. Nonetheless, the objects of the `Buildings` cannot be moved during the simulation runtime, and, if a mobility model makes a user enter and exit a building, its indoor/outdoor status is not properly handled.[1] With respect to the integration with mobility models, they would benefit from a tighter integration with the buildings, as proposed in [15].

Mobility models: as stated in Section 2.3, the realistic modeling of the mobility patterns of user terminals is fundamental for a proper evaluation of the network performance. The ns-3 `mobility` module provides several classes implementing different mobility models, either random, e.g., `RandomWalk2D`, `GaussMarkov`, `RandomWaypoint`, or deterministic, e.g., `ConstantVelocity`, `Waypoint`. While the deterministic models can be used only when the mobility patterns of the moving terminals are completely known, the random models provides the possibility to account for the user mobility in a statistical way. However, in some cases they may be too general to properly consider the complex temporal and spatial correlations which characterize the human motion [5], and may not be suitable to simulate emerging use cases, such as vehicular and aerial deployments [7]. As already mentioned, the device rotation could be even more problematic than mobility alone in high frequency communications. A basic implementation of the device rotation could simply follow the direction in which the user is moving. To further increase the realism, a choice of statistical models for device rotation could also be added. To integrate the device rotation with the beamforming and channel modeling, a complete framework should be introduced, thus separating the global frame of reference from local ones.

[1] https://www.nsnam.org/bugzilla/show_bug.cgi?id=3018

Scalability: there is a trade-off between the accuracy and the complexity of the simulations. For example, the high level of detail in the scheduling of synchronization signals for the cellular stacks may yield an excessive overhead in terms of simulation complexity. Nonetheless, this could be avoided when the users are not using the network resources (e.g., in the case of machine-to-machine communications). Therefore, it makes sense to investigate and implement mechanisms that allow the simulation to reduce the number of scheduled events and consequently the simulation runtime, e.g., in case of bursty and sporadic traffic. Even though it should be noted that this approach is not always possible (e.g., in scenarios with non-bursty and heavy traffic), finding scalable approaches where the simulation complexity is minimized according to the simulated scenario is a worthwhile research direction.

4 CONCLUSIONS

In this paper, we described the simulation of cellular networks with ns-3, outlining the main characteristics of the involved simulation models. Then, we discussed the limitations which ns-3 poses to the simulation of cellular systems, and provided some future directions which can be pursued to meet the open issues.

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