LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-CONF-773337

S3: the Spectrum Sharing Simulator

P. D. Barnes, M. D. Bielejeski, D. R. Jefferson, S. G. Smith, D. G. Wright, L. Giupponi, K. Koutlia, C. Harper

May 1, 2019

Workshop on ns-3, Next-Gen Wireless
Florence, Italy
June 17, 2019 through June 21, 2019

S3: the Spectrum Sharing Simulator

Peter D. Barnes, Jr.†
Matthew D. Bielejeski,
David R. Jefferson,
Steven G. Smith,
David G. Wright
Lawrence Livermore National Laboratory (LLNL)
Livermore CA USA
pdbarnes, bielejeski1, jefferson6, sgsmith, wright97 @llnl.gov

Lorenza Giupponi,
Katerina Koutlia
Mobile Networks Department
Centre Tecnològic de Telecomunicacions de Catalunya (CTTC)
Castelldefels Spain
lorenza.giupponi, katerina.koutlia @cttc.es

Colby Harper
Pathfinder Wireless
Seattle WA USA
colby@pathfinderwireless.com

ABSTRACT

Changes in U.S. spectrum licensing are predicated on managing shared use of spectrum bands between commercial and government uses, potentially indefinitely. This has created a need for accurate tools to estimate mutual interference between commercial and government systems using vastly different technology, over a wide range of spatial scales, numbers of transmitters, and using very complicated protocols such as LTE and evolutions operating over multiple bands simultaneously. Current interference simulation tools are inadequate. The Spectrum Sharing Simulator Project is enhancing the open source ns-3 simulator to support much larger problems, easier parallel execution, and enhanced LTE/NR models to track 3GPP standard development.

CCS CONCEPTS

Computing methodologies • Modeling and simulation
• Simulation types and techniques • Discrete-event simulation
• Wireless access points, base stations and infrastructure

1 INTRODUCTION

The U.S. Federal Communications Commission has developed rules for the reallocation and subsequent auction of frequency bands previously dedicated to government use. The new intended use of these bands is for licensed advanced wireless services (AWS), expected to be primarily wireless broadband communications utilizing the 3GPP standards such as LTE (Long Term Evolution) and New Radio (NR)*.[1, 2] The third such auction (AWS-3) closed in January 2015. For the first time, a portion of the auction proceeds were set aside to institute sharing regimes with Federal systems which cannot be relocated. To manage early entry of new licensees into the bands, and coordinate shared use, which in some cases may be permanent, U.S. Government Departments have instituted various assessment processes, with the goal of ensuring interference-free operation between Federal and commercial systems as they enter the band.

Key to these analysis processes is understanding in detail how LTE operation potentially leads to interfering emissions: Which specific LTE protocol signals are potentially most harmful, in aggregate? Can configuration or operation of specific LTE sectors be altered to reduce or limit harmful emissions near victim receivers? How do deployment environment (ranging from dense urban canyons to rural) and terrain impact emissions? What about temporary high-density deployments, such as around sporting events and concert venues? Given understanding of individual sectors, how should one aggregate interference from all sectors and handsets in a large metropolitan region?

In this paper we introduce S3: the Spectrum Sharing Simulator. The goal of the S3 Project is to enhance the open-source ns-3 simulator in order to address these questions.[3] This requires significant new development of ns-3 as a parallel discrete event simulator, new methods to model shared channels in a distributed simulation, and implementation and validation of new interesting LTE/NR features within the ns-3 model space to keep pace with successive 3GPP releases..

This paper is organized as follows: section 2 provides background on the motivation for this project, and the types and scale of wireless simulation required; section 3 discusses existing simulation capabilities and their limitations; section 4 introduces S3: the Spectrum Sharing Simulator; section 5 discusses enabling technologies in simulation and LTE modeling that make this project possible; and finally section 6 concludes with a summary of the project development timeline.

†Corresponding author

Workshop on Next-Generation Wireless with ns-3, June 2019, Florence ITALY

* We use the shorthand "LTE" to stand for LTE, LTE-Advanced and 5G-New Radio (5G-NR).LTEPro, and "NR" to stand for 5G-New Radio.

2 BACKGROUND

Of particular interest for this work are the assessments developed for protecting US Department of Defense (DoD) systems, since the DoD Defense Spectrum Organization (DSO) is the sponsor of the S3 Project. DSO is responsible for enabling early entry of AWS-3 licensees into the band and managing permanent sharing regimes for DoD systems which will continue to operate in band indefinitely. In particular, the DSO Spectrum Sharing Test and Demonstration Program (SST&D) has two objectives: facilitate expedited and expanded early entry of licensee deployments into the band; and identify, assess, test/demonstrate, and operationalize coexistence techniques, interference mitigation, and other spectrum sharing enablers that support increased sharing between 4G/5G and incumbent DoD systems.

There are two aspects of this problem. In one case, LTE emits transmissions that may potentially cause harmful interference to government receivers. In the other case, LTE systems may be the recipients of harmful interference from government transmitters. For the case where the LTE system is viewed as the emitter, the SST&D Program is attempting to determine how the LTE aggregate emissions behave over a wide, metropolitan area and over extended periods of time. Special events that might change LTE system behavior will also be modeled and simulated. The goal is to build up a substantial body of knowledge on LTE system behavior over a wide range of conditions. Many of these conditions can only be simulated and cannot be measured. This makes a dependable and validated simulation model critical to understanding all aspects of LTE system performance.

3 EXISTING WIRELESS SIMULATORS

There are two primary challenges for modeling interference in large scale wireless models: first, simulating many times many base stations (eNodeB) and handsets (UE) utilizing a single shared channel, including full node mobility throughout a large metropolitan region with a million UEs; and second, accurately modeling interference from this large set of spatially and temporally distributed transmitters. Neither of these is particularly difficult if the entire model scenario can be run in a single process memory space, but this becomes intractable beyond a few dozen eNodeB and few thousand UEs; executing such scenarios would be excruciatingly slow and require vastly more system memory than commonly available.

While there are a variety of LTE simulators, most are single process only; and the few that support distributed (multi-process) execution have not been demonstrated at anything near the required scale. For example, LTE-Sim is a standalone LTE simulator, but works only in a single process space.[4] OMNet++ is a general purpose discrete event simulator with a limited parallel execution capability which has been tested to a limited scale.[5] When run sequentially OMNet++ and ns-3 (see below) have similar execution and memory performance.[6] The INET module for OMNet++ supports network simulation generally. This module has been enhanced with threading support and demonstrated speedups of 30% with 10 threads.[7] A different effort added distributed parallelism support to INET and achieved speedup of 14 on five processors.[8]

By contrast, ns-3 has been shown to scale to very large numbers of simulated nodes (500K) and a large number of processors (300), at least for wired networks. [3, 9-13] ns-3 is a research-oriented, discrete-event network simulator, written in C++ with Python bindings. It has been under continuous development since 2005, courtesy of funding from the US NSF, INRIA in France, and several other public and private organizations. ns-3, and its predecessor ns-2 are the most frequently cited tools used in computer network research.[*] ns-3 is a complex, multi-author piece of software that has undergone 29 software releases since 2008 and has been used for thousands of research papers and projects. It is highly portable across multiple Linux and Unix variants, as well as Mac OS X. A Windows port is in development. Consequently, the S3 Project is based on enhancing the ns-3 simulator to address the challenges described above.

4 S3: THE SPECTRUM SHARING SIMULATOR

The objective of the S3 Project is to develop a scalable (parallel, optimistic, dynamic load-balancing) resource block-level discrete event simulator ("the Simulator") capable of analyzing mutual interference between current and near future LTE 4G/LTE-Advanced/5G-New Radio (LTE) cell phone systems and Department of Defense (DoD) assets. Also as part of this projec- the Simulator will be used: to cross-validate with the UE equivalent isotropic radiated power (EIRP) cumulative distribution curves developed by the U.S. Commerce Department for urban and rural (point) scenarios (CSMAC)[14]; to conduct parameter studies around the CSMAC points; to extend those studies to include dynamic features of LTE, including behavior driven by eNodeB scheduler algorithms; analyze regional-scale scenarios; and analyze scenarios using LTE technology in DoD tactical operations. An integral part of this work will be to validate results against real-world data acquired by SST&D, in addition to cross-validating against the CSMAC curves. To support these analyses in real-world settings and at regional scale the Simulator will be developed to model: real propagation effects over real terrain; specific dynamic features of current or near-future LTE standards; and LTE interference and mitigating control features between modeled LTE cells in large scale scenarios. Each major modeling feature will be validated against SST&D data. In order to provide the best execution performance, the Simulator will be a parallel discrete event simulator (PDES) using "optimistic" synchronization and supporting dynamic load balancing across the computing cluster.

The ns-3 LTE module, commonly referred to as LENA, combines a simulated channel and physical layer model with an implementation of the LTE and EPC protocol stack that closely follows 3GPP specifications. Most of the current version of LENA was developed between 2011 and 2013 as part of an industrial project funded by Ubiquisys Ltd. (now part of Cisco), and carried out by CTTC, with the aim of developing an open-source product-oriented LTE/EPC Network Simulator, allowing LTE small/macro cell vendors to design and test Self Organized Network (SON) algorithms and solutions.

[*] Based on a recent survey of journal and conference papers published in 2016 in the IEEE and ACM Digital Libraries

In the current version ns-3 models LTE R13 at the resource block level (0.5 ms and 180 kHz, typically), with nearly arbitrary time and frequency resolution for asynchronous interference/noise sources.

To support regional-scale scenarios the Simulator will be capable of representing

- Thousands of eNodeB nodes, with 3-10 sectors, including pico/femto cell configurations.
- A variety of eNodeB antenna configurations
- More than one million mobile UEs
- Dynamic closed loop power control
- A variety of uplink scheduling algorithms
- Multiple bandwidth options and baseband frequencies
- Variable and dynamic UE offered traffic loads, and mobility patterns, including hand-off between eNodeBs
- Dynamic effective cell geometry, including effects of topography and propagation

This scale will also require new configuration tools to manage such large numbers of eNodeBs and UEs. These goals represent one to three orders of magnitude improvement in current LTE simulation capabilities, compared to any currently available simulation platform, including the current release of ns-3.

5 ENABLING TECHNOLOGIES

The scope and scale required to address this problem space is daunting, however there have been a number of developments in parallel discrete event simulation and LTE models which make this scope feasible.

5.1 Parallel Discrete Event Simulation

One of the key issues in PDES is synchronization of the multiple processes so that the parallel execution produces exactly the same results as would have been obtained in a sequential execution. The main difficulty is managing execution of events in the local queue with respect to event messages being sent by other processes. Historically there have been two approaches to this problem: conservative execution, in which the simulation processes coordinate so that each process can determine which events in its queue are safe to execute; and optimistic execution, in which each process speculatively executes events, and reverses those executions ("rolls back") if it turns out that an event sent by a remote process should have been executed first.[16]

Generally optimistic simulation executes faster overall than conservative simulation because of the reduced synchronization overhead, despite the need for additional code and storage to support event roll back, which has been a major impediment. (On the other hand, conservative execution requires additional information from the model ("lookahead"), which is often difficult to extract.) We have developed a compiler-assisted approach, dubbed Backstroke, which automatically instruments sequential model code to support roll back.[17, 18] This tool supports all C and C++ constructs, including the C++ Standard Template Library. Backstroke implements a source code to source code transformation which adds instrumentation to assignment statements in model code and provides a library to record those assignments and reverse them when necessary. With Backstroke one writes just the sequential model code yet obtains the ability to execute it optimistically.

Recently we have generalized the conservative/optimistic divide into a Universal Virtual Time (UVT) approach, where each simulation process determines dynamically whether to execute the next event conservatively or optimistically.[19] This has the potential to be faster than either alone. With UVT and Backstroke a model developer can focus on writing correct sequential model code, and and the simulator will enable optimistic execution. As one gains experience with the model one can add the lookahead information and enable conservative execution, which will now act as an accelerator.

The second major issue in large scale PDES simulation is dynamic load balance. Even with a very well-behaved Gaussian distributed work load, across 1M objects about 1000 will be 3-sigma behind. Charm++ offers an alternative messaging infrastructure (compare to the MPI support in ns-3 now) which supports dynamic object migration for load balancing.[20] This has been shown to be an excellent platform for PDES.[21]

For S3 we plan to re-engineer the core simulator in ns-3 to support Backstroke and UVT, running over Charm++. Prior work has established that only a limited number of features in ns-3 will need to be refactored.[22] Further enhancements to underlying ns-3 infrastructure will include enhanced propagation and clutter models, and a new approach to modeling distributed interference based on the fast multipole method.

5.2 LTE Model Development

We are extending ns-3 to model additional and proposed LTE standards, such as closed loop power control, time division duplex, inter-cell/inter-cluster coupling and interference estimation, evolution of the advanced internode coordination capabilities, variable and dynamic cell geometry, high fidelity X2 interface, mobile eNodeBs, New Radio numerologies and flexible TTI, full dimension MIMO, carrier aggregation, operation in shared and unlicensed spectrum, network slicing, LTE-Advanced, new types of UE such as dongles and IoT devices, LAA[23] and 5G technology, and a variety of eNodeB scheduler algorithms. For example, these technologies anticipate refining the LTE scheduling unit, from the current 0.5 ms resource block down as small as the symbol level, or 71 µs., representing an increase in complexity of one to two orders of magnitude.

Recently, multiple lines of development of LTE models for ns-3 have emerged. A significant enhancement was announced late last year which adds support for extended RRC functionalities, compared to those previously supported in ns-3, and mainly oriented to simulate RRC CONNECTED state. Examples of these features are support for radio link failure, handover failure, cell reselection, and long awaited support for IDLE mode, paging, *etc.* These features are being merged into the release version of ns-3.[24]

In parallel, two groups have been developing models for LTE 5G features. The NYU mmWave module is focused on physical layer modeling in the mm bands, and leverages ns-3 LENA for the higher protocol layers.[25] This has been extended to protocol layers by CTTC. We are leveraging the mmWave module, along with the RRC work mentioned above, to develop and release a comprehensive new model of LTE and its evolution, New Radio, within ns-3.[26]

6 SUMMARY

Bringing together Backstroke, UVT, and Charm++ the S3 Project will transform ns-3 into an easy to use full-featured PDES simulator, and provide the platform required for regional analysis of spectrum sharing problems. At the same time, the Project will continue the development of LTE and NR models in ns-3 to keep pace with evolution of the 3GPP standards and proposals well into the future.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

REFERENCES

[1] 3rd Generation Partnership Project 2 (3GPP2), *Study on New Radio (NR) access technology (Release 14)*. TR 38.912, 3GPP, 2017, https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3059.

[2] 3rd Generation Partnership Project 2 (3GPP2), Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description; Stage 2. TS 36.300, 3rd Generation Partnership Project 2 (3GPP2), 2017, https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=2430.

[3] Carneiro, G. J. A. M., *NS-3: network simulator 3*. Presentation, Universidade do Porto, 2010.

[4] Virdis, A., et al., "Simulating LTE/LTE-Advanced networks with SimuLTE," in *Proceedings of the SIMULTECH 2014* (Vienna Austria, August 28-30, 2014, 2016). Springer, https://telematics.poliba.it/index.php?option=com_content&view=article&id=28&Itemid=203&lang=en.

[5] Sekercioglu, Y. A., et al., "PARALLEL SIMULATION MADE EASY WITH OMNeT++," in *Proceedings of the 15th European Simulation Symposium* (2003).

[6] Weingartner, E., et al., "A performance comparison of recent network simulators." *Ieee Icc*2009), 1287-1291, http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5198657&tag=1.

[7] Mavromatis, I., et al., "Parallel Implementation of the OMNeT++ INET Framework for V2X Communications," in *Proceedings of the IEEE Vehicular Networking Conference* (Taipei Taiwan, December 5-7, 2018, 2018). IEEE, https://arxiv.org/abs/1811.03394 http://www.ieee-vnc.org.

[8] Stoffers, M., et al., "Enabling Distributed Simulation of OMNeT++ INET Models," in *Proceedings of the OMNeT++ Community Summit* (Hamburg Germany, September 2, 2014, 2014), https://arxiv.org/abs/1409.0994.

[9] Baldo, N., et al., *ns-3 LTE Model*. ns-3 Project, 2017, https://www.nsnam.org/docs/models/html/lte.html.

[10] Baldo, N., et al., *LENA: LTE-EPC Network simulAtor*. CTTC, Barcelona, 2017, http://networks.cttc.es/mobile-networks/software-tools/lena/.

[11] Nikolaev, S., et al., "Pushing the envelope in distributed ns-3 simulations: one billion nodes," in *Proceedings of the Proceedings of the 2015 Workshop on ns-3* (Barcelona, Spain, 2015). ACM.

[12] Nikolaev, S., et al., "Performance of Distributed ns-3 Network Simulator," in *Proceedings of the SIMUTools 2013, the 6th International ICST Conference on Simulation Tools and Techniques* (Cannes, France, March 5-7, 2013).

[13] Smith, S., et al., "Improving per processor memory use of ns-3 to enable large scale simulations," in *Proceedings of the Proceedings of the 2015 Workshop on ns-3* (Barcelona, Spain, 2015). ACM.

[14] *Commerce Spectrum Management Advisory Committee: Final Report, Working Group 1 – 1695-1710 MHz Meteorological-Satellite*. Commerce Department, Washington, D.C., 2013, https://www.ntia.doc.gov/files/ntia/publications/wg-1_report_v2.pdf.

[15] Fujimoto, R., *Parallel and Distributed Simulation Systems*. John Wiley & Sons, 2000.

[16] Fujimoto, R. M., "Parallel Discrete Event Simulation." *Commun. ACM*, 33, 10 (Oct 1990), 30-53, <Go to ISI>://A1990EB71500011.

[17] Schordan, M., et al., "Automatic Generation of Reversible C++ Code and Its Performance in a Scalable Kinetic Monte-Carlo Application," in *Proceedings of the PADS 2016: ACM SIGSIM Conference on Principles of Advanced Discrete Simulation (PADS)* (Banff, Canada, May 15-18, 2016, 2016). ACM.

[18] Schordan, M., et al., "Reverse Code Generation for Parallel Discrete Event Simulation," in *Proceedings of the 7th Conference on Reversible Computing* (Grenoble, France, July 16-17, 2015, 2015).

[19] Jefferson, D. and Barnes Jr., P. D., *Virtual Time III: unification of conservative and optimistic synchronization in parallel discrete event simulation*. Reno, Nevada, 2017.

[20] Kalé, L., *Charm++*. UIUC, Urbana-Champaign, IL, 2013, http://charm.cs.uiuc.edu/research/charm/.

[21] Mikida, E., et al., "Towards PDES in a Message-Driven Paradigm: A Preliminary Case Study Using Charm++," in *Proceedings of the PADS 2016: ACM SIGSIM Conference on Principles of Advanced Discrete Simulation (PADS)* (Banff, Canada, 2016).

[22] Kim, E. and Riley, G., "Automatic State Saving and Rollback in ns-3," in *Proceedings of the SIGSIM PADS 2017* (Singapore, 2017). ACM, https://dl.acm.org/citation.cfm?doid=3064911.3064925.

[23] Giupponi, L., et al., "Simulating LTE and Wi-Fi Coexistence in Unlicensed Spectrum with ns-3,"2017), https://arxiv.org/abs/1604.06826.

[24] Oleinichenko, O., et al., Enhanced ns-3 LTE module with extensive RRC_IDLE mode features, ns-3 Developers Mailing List, 2018, https://mailman.isi.edu/pipermail/ns-developers/2018-August/014475.html.

[25] Mezzavilla, M., et al., "5G mmWave Module for the ns-3 Network Simulator," in *Proceedings of the 18th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*. (2015).

[26] CTTC, 5G-LENA, Barcelona, Spain, 2019, https://5g-lena.cttc.es.