On the Reproduction of Real Wireless Channel Occupancy in ns-3

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ABSTRACT

In wireless networking R&D we typically depend on simulation and experimentation to evaluate and validate new networking solutions. While simulations allow full control over the scenario conditions, real-world experiments are influenced by external random phenomena and may produce hardly repeatable and reproducible results, impacting the validation of the solution under evaluation. Previously, we have proposed the Trace-based Simulation (TS) approach to address the problem. TS uses traces of radio link quality and position of nodes to accurately reproduce past experiments in ns-3. Yet, in its current version, the TS approach is not compatible with scenarios where the radio spectrum is shared with concurrent networks, as it does not reproduce their channel occupancy.

In this paper, we introduce the InterferencePropagationLossModel and a modified MacLow to allow reproducing the channel occupancy observed in past experiments using Wi-Fi. To validate the proposed models, the network throughput was measured in different experiments performed in the w-iLab testbed, controlling the channel occupancy introduced by concurrent networks. The experimental results were then compared with the network throughput achieved using the improved TS approach, the legacy TS approach, and pure simulation, validating the new proposed models and confirming their relevance to reproduce experiments previously executed in real environments.

CCS CONCEPTS
• Networks → Network simulations; Network experimentation; Network measurement; Mobile networks; Mobile ad hoc networks; Protocol testing and verification; Network protocol design.

KEYWORDS
ns-3, Mobile Network Simulation, Trace Based Simulations, Reproducibility of Experimental Conditions, Perpetuation of Real-World Mobile Testbeds, Offline Experimentation, Channel Occupancy

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1 INTRODUCTION

Wireless networking R&D depends on simulation and experimentation to evaluate and validate new networking solutions. While simulations allow full control over the scenario conditions (e.g., number of nodes, propagation loss, mobility, duration of experiment, obstacles), real-world experiments are influenced by external random phenomena (e.g., noise, interference, multipath, channel occupancy) and may produce hardly repeatable and reproducible results. The lack of repeatability and reproducibility directly impacts the validation of the solution under evaluation.

Motivated by our hands-on experience with testbeds operating in emerging scenarios such as aerial [10] and maritime [2], we have been developing the Trace-based Simulation (TS) approach to enable repeatable and reproducible wireless networking experimentation using ns-3 [6][7]. The TS approach introduces new mechanisms to 1) capture the execution conditions of an experiment and 2) enable its repetition and reproduction using ns-3 by relying on its good simulation capabilities from the MAC to the application layer. The results so far, including a large scale evaluation using the Fed4FIRE+ [4] community wireless testbeds [9], show that the TS approach is valid and achieves accurate reproduction of past experiments, even if the testbed becomes unavailable. The TS approach offers a special advantage over Pure Simulation (PS) approach in mobile scenarios, where the propagation loss characteristics are constantly changing and it is not possible to fine-tune a traditional PropagationLossModel to be accurate throughout the movement of the nodes. Nevertheless, the TS approach also has limitations [8] such as the inability to reproduce the channel occupancy caused by concurrent radio transmissions from nodes that were in radio...
range but did not belong to the experiment we are willing to reproduce. This is a especially relevant limitation considering that in real scenarios it is very common to find multiple overlapping Wi-Fi networks.

The original contributions of this work are two-fold: 1) the improved version of the TS approach, now using a new ns-3 InterferencePropagationLossModel and an updated Wi-Fi MacLow to reproduce the Channel Occupancy caused by other nodes not belonging to the experiment; 2) further validation of the TS approach, now focusing on non-controlled environments where reproducing the channel occupancy in ns-3 (on top of the radio link quality and mobility of nodes) is essential to maintain an accurate reproduction of past experiments.

The paper is structured as follows. In Section 2 we present the Related Work that directly influenced the contributions presented in this paper. In Section 3 we present the new InterferencePropagationLossModel and the updated MacLow, including their implementation details, in order to reproduce the channel occupancy of past experiments. In Section 4 we evaluate the new version of the TS approach, based on the models presented in Section 3, through experiments with controlled channel occupancy executed in the w-iLab testbed. Finally, in Section 5 we draw the conclusions and refer the future work.

2 RELATED WORK

The work presented in this paper is directly related to previous publications addressing the repeatability and reproducibility of past experiments using the TS approach, which is based on trace-based ns-3 simulation models.

In [6] TS concept was presented and applied for the first time to reproduce a 2000 seconds long wireless networking experiment between an Unmanned Aerial Vehicle (UAV) and a Base Station (BS). The UAV flew over the sea up to 7 km away from the BS and at speeds of up to 400 km/h. The high cost of operation, weather constraints, and all the complex logistics involved were seriously impairing the evaluation of the communications solution. Moreover, because of the complex characteristics of the scenario, the pure simulation models of ns-3 were not able to accurately simulate those conditions. By recording traces of link quality (Signal-to-Noise ratio) and the position of nodes, and using the proposed TraceBasedPropagationLossModels, the authors showed that it was possible to accurately repeat and reproduce the experiment in ns-3 without access to the testbed. The TS approach helped not only to improve the networking solution, but also other components that depended on communications to work such as the data publishing components on-board the UAV and the subscriber components connected to the BS node. By then, the TS approach supported point-to-point radio links, an SNR sampling resolution of one per second, and was evaluated using a fixed PHY-rate (6 Mbps) link.

In [7] the TS approach was evolved to support multiple-access scenarios. The improved TraceBasedPropagationLossModel was tested in a laboratory testbed, showing that even in controlled environments the TS approach presented clear benefits over pure simulation when reproducing past experiments. This was mainly due to the non-negligible radio link asymmetry and clear RX sensitivity and TX power differences between nodes using identical Wi-Fi cards. In this paper it was also shown that using High SNR Sampling Rate (one SNR sample per packet received instead of one SNR sample per second) was vital to reproduce the throughput more accurately when using auto-rate adaptation (Minstrel). Although the paper showed very promising preliminary evaluation results of the improved TS approach, a large scale evaluation was lacking.

To overcome this limitation, the large-scale evaluation of the TS approach using the community wireless testbeds made available by the Fed4FIRE+ federation was considered [4] as part of the SIMBED F4Fp-OC3 European research project. Hundreds of Wi-Fi experiments were performed in point-to-point and multiple-access scenarios, as well as considering static and mobile nodes. Those experiments were then reproduced in ns-3 using the TS approach. The results [9] showed the clear value of the TS approach for accurately reproducing the past experimental conditions. However, some limitations were identified (e.g., lack of channel occupancy reproduction, which affects scenarios where experiments share the radio spectrum with other concurrent networks) and a plan was devised in [8] to overcome them towards a better simulation-experimentation synergy using ns-3.

The present work focuses on overcoming the TS approach limitation regarding the reproduction of the channel occupancy [8] registered in past real experiments, building on top of the proven strengths of the TS approach. Supporting the reproduction of channel occupancy has become increasingly important in Wi-Fi networks, due to their overlapping deployments, namely in dense urban scenarios. In these scenarios, multiple concurrent networks use overlapping spectrum, therefore interfering among themselves and significantly lowering the expected throughput. Even if the ns-3 PS models are perfectly fine-tuned to reproduce the real RF environment conditions, the channel occupancy alone can significantly affect the performance evaluation, resulting in incomparable results between simulation and experimentation.

The closest related work we could find was related to the reproducibility of experimental results in IoT testbeds. In [1] the authors present a methodology to test whether the laboratory results are realistic enough to be considered valid and to allow their reproduction using the same or other testbed. For that purpose, they capture traces of the Packet Delivery Ratio (PDR) and Received Signal Strength Indication (RSSI) of the radio links along the time by running a specific firmware in the IoT nodes. They suggest as future work to feed simulators with such captured radio link quality data to reproduce more accurate simulations. While in IoT networks PDR and RSSI may be enough to reproduce results very close to the ones of original past experiments, in Wi-Fi the channel occupancy also has a significant impact in the performance of the networks due to the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. In CSMA/CA, when a node senses a busy medium it refrains from immediately transmitting new packets that would cause collisions, lowering the PDR. Therefore, reproducing the channel occupancy of real experiments is relevant for the trace-based simulation of Wi-Fi networks.

To the best of our knowledge, the work presented herein is the first attempt to use traces of past real-world Wi-Fi experiments with the objective of reproducing the channel occupancy of concurrent networks in simulation. The introduction of this new functionality
represents a clear improvement over the previous version of the TS approach.

3 CHANNEL OCCUPANCY MODEL

3.1 Background

Following the work in [6] and [7], the new proposed model builds on top of the same trace-based simulation principles, now focusing on supporting scenarios with shared radio spectrum with concurrent networks. In the model, channel occupancy only represents the contribution of nodes from other networks occupying the shared medium while our network is operational and also attempting to transmit. This concurrent usage of spectrum has 2 main impacts in our transmission: 1) at the sender, where its transmission will be hindered when attempting to access the medium; 2) at the receiver, where hidden nodes may cause interference with the transmitted packet and, thus, it’s loss. For the sake of completeness, we now refer to the goal of the channel occupancy model and the most relevant aspects taken into account in its design.

- **Goal.** The goal of this work is to measure the real world channel occupancy caused by non-controlled networks, which influence the performance of our network, and reproduce this behaviour in ns-3 trace-based simulations. As the TS approach already accurately simulates and reproduces the performance of our network without external interference, this work only focuses on reproducing the impact of external networks in our own network. Because those networks are unknown and not controllable, they cannot be simulated at the same level as our network, but rather its effect is taken into account.

- **Variables to be collected.** In order to reproduce real-world channel occupancy, each node of the network needs to measure how long it sensed the medium busy due to activity of other networks, and store these measurements in a “busy” trace file. Real wireless cards from Qualcomm Atheros (ath9k/ath10k-based drivers) report three values: 1) the total time the wireless card has been active; 2) the time it spent active (active), the time it sensed the medium busy, either by the current network or other networks (busytot) and 3) the time it spent transmitting. Assuming that the receiver and sender are in radio range, the sender’s active will be accounted in the receiver’s busytot. Furthermore, assuming that all nodes of the current network are in radio range of each other, the total transmission time of the current network will be accounted in the busytot of all nodes, so the remaining busytot is considered to be the transmission time from other networks sensed at node i (busytot), defined by Equation 1, where n represents the number of nodes in the current network. These values are measured every second (1000 ms) and presented in ms.

\[
\text{busytot} = \text{busytot} - \sum_{j=0}^{n} (t_{x_j})
\]

Each node’s Channel Occupancy (CO) is calculated every second (1000 ms), and represents the percentage of busytot measured by node i during those 1000 ms, using Equation 2:

\[
CO_i = \frac{\text{busytot}_i}{1000}
\]

3.2 Channel Occupancy

Channel Occupancy is defined here as the proportion of time a node sensed the medium occupied by networks other than the Wi-Fi network it is associated with (current network). To measure it, each node’s wireless card reports 1) the time it spent active (active), 2) the time it sensed the medium busy, either by the current network or other networks (busytot) and 3) the time it spent transmitting. Assuming that the receiver and sender are in radio range, the sender’s active will be accounted in the receiver’s busytot. Furthermore, assuming that all nodes of the current network are in radio range of each other, the total transmission time of the current network will be accounted in the busytot of all nodes, so the remaining busytot is considered to be the transmission time from other networks sensed at node i (busytot), defined by Equation 1, where n represents the number of nodes in the current network. These values are measured every second (1000 ms) and presented in ms.

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\[
CO_i = \frac{\text{busytot}_i}{1000}
\]

3.3 Receiver’s Channel Occupancy

As previously stated, to reproduce the receiver’s channel occupancy, a new propagation loss model was developed, the InterferencePropagationLossModel, which blocks packet reception according to the receiver’s channel occupancy observed in the real experiment.

- **Channel Occupancy Simulation Settings.** As in [7], the following settings should be taken into account: 1) TX Power End, TX Power Start and TX Gain; 2) RX Gain; 3) WiFi Standard, WiFi Mac, Frequency, Channel BW and Remote Station Manager; 4) Propagation Delay; 5) Propagation Loss; 6) Error Ratio Model; 7) Data Mode and Control Mode and 8) Mobility Model. Furthermore, to reproduce channel occupancy, the proposed propagation loss model should be used, as well as the modified Mac layer. ns-3 uses a linked list of propagation loss models, so it is advised that the InterferencePropagationLossModel is used at the end of this chain to effectively block packet reception, as expected.
uses it during its initialization to process the files of each node and map the channel occupancy samples to simulation time in \textit{m\_occupancyMap}.

- \textbf{m\_occupancyMap} - maps each \textit{<node id, time>} pair to a channel occupancy sample, initialized in the model’s constructor with \textit{LoadBusyNode}, using the \textit{node id} file name stored in \textit{m\_filenames}.

- \textbf{m\_random} - uniform random variable used to decide whether the receiver can receive the transmitted packet. In each \textit{DoCalcRxPower} call, if the receiver has a free medium, then the transmission power (\textit{txPowerDbm}) is returned, so the transmission remains unaffected. Otherwise, with an occupied medium (interference/collision), a low reception power (\textit{rxPowerDbm}) is returned, so that the receiver is unable to properly decode the transmitted packet, blocking the transmission. This behaviour is described in Equation 3, where \(CO_i\) represents the channel occupancy observed by the node at simulation time \(i\).

\[ \text{rxPowerDbm} = m\_random < CO_i \? -1000 : txPowerDbm \] (3)

### 3.4 Sender’s Channel Occupancy

**Figure 2:** Class Diagram of the Modified \textit{MacLow}

Although reproducing the channel occupancy at the sender node (modified Wi-Fi \textit{MacLow}) and at the receiver node (new \textit{InterferencePropagationLossModel}) represents a clear improvement over the previous TS approach, the current improved version has the following known limitations.

- \textit{InterferencePropagationLossModel} does not support packet aggregation. This is due to the ns-3 implementation of IEEE 802.11 packet aggregation, where the preamble is sent with the first packet of the aggregate frame, both experiencing the same probability of being lost. When the preamble is lost, the whole aggregate frame is lost. Thus, when using Wi-Fi standards such as IEEE 802.11n/ac, which use packet aggregation by default, the \textit{InterferencePropagationLossModel} introduces a much higher packet loss than expected. In reality, the probability of losing the preamble is much lower than the frames themselves.

- Distribution of Channel Occupancy between the sender and receiver nodes is not automatically performed. Currently the TS approach supports the reproduction of channel occupancy at the sender and receiver nodes. Occupancy at the sender represents the percentage of time, for each second, that the sending nodes sensed the medium busy, therefore refraining to transmit and not causing packet losses. Channel occupancy at the receiver, on the other end, is intended to be used for cases where hidden nodes from the sender or additional interference is detected at the receiver node, causing packet loss. The problem is that the channel occupancy traces from the real experiments do not distinguish between "commonly sensed" channel occupancy and interference at the receiver node, so currently there is no mechanism to distribute the occupancy levels between the two models. For example, if all Wi-Fi nodes of our experiment are commonly affected by the same (in-range) concurrent network, causing equivalent channel
occupancy to all of them, then only the modified MacLow should be used. The InterferencePropagationLossModel shall only be used at the receiver for the additional (comparatively to the sender) channel occupancy reported at the receiver caused by nodes hidden from the sender and possible additional interference. For example, if the sender and receiver nodes report 50% and 75% of channel occupancy, respectively, the InterferencePropagationLossModel should be used at the receiver to reproduce the additional 25% of channel occupancy not reported by the sender. In the current version of the TS approach, the experimenter has to manually assess when to use and enable the InterferencePropagationLossModel.

InterferencePropagationLossModel may produce higher medium inefficiency than expected. This model directly reproduces the channel occupancy as random time slots during which all frames are not successfully received at a specific node, causing ACK timeouts and retransmissions from the sender nodes. These ACK timeouts, and consequent retransmissions, have two possible causes: 1) when a data frame is lost, the receiver does not generate an ACK response frame, and the sender waits for the ACK timeout before retransmission; 2) when the data frame is successfully received, the receiver generates an ACK, but if the ACK is the one lost during propagation, the sender will also wait until the ACK timeout expires, after which a new re-transmission occurs. In a real experiment the second scenario is less probable than the first one due to the fact that the ACK frames are very small and are sent at a lower PHY rate than the data frames (lower BER). Conversely, using the InterferencePropagationLossModel both scenarios end up with equivalent probability of happening, causing more retransmissions than expected, resulting in higher than expected medium inefficiency. Nonetheless, does not introduce a significant impact as this model is only used specifically for scenarios where additional interference and hidden nodes are only sensed by the receiver.

Only evaluated in Wi-Fi. The modified Wi-Fi MacLow and the InterferencePropagationLossModel were specifically developed and evaluated using Wi-Fi networks. The same principles discussed here may be applied to other technologies, but even if the models are easily reusable (e.g., InterferencePropagationLossModel) their impacts on the operation of other technologies should be carefully assessed.

4 EVALUATION OF THE CHANNEL OCCUPANCY MODEL

To validate the new model and the implemented modifications in ns-3, two tests were performed: 1) simulation based on traces composed of synthetic predefined channel occupancy values, in order to assess whether the results obtained in ns-3 using the new model are the expected ones with respect to the enforced channel occupancy values (e.g., for a channel occupancy of 50% we expect near 50% of the maximum throughput); 2) using a Fed4FIRE+ testbed [4] and considering a controlled scenario with two Wi-Fi communicating nodes (the experiment we want to reproduce in ns-3), and an outside Wi-Fi network causing controlled interference (the one that is accounted in the channel occupancy/’busy’ trace files). In each simulation, the sender’s and receiver’s channel occupancy were first tested independently, one simulation using only the InterferencePropagationLossModel and another using only the modified MacLow. Then, both models were tested together.

4.1 Synthetic Data Test

To test each implementation separately, a test was devised comprised of two nodes (A and B), starting with unidirectional iperf UDP flows, A→B and B→A, and then a bidirectional flow, A↔B, each flow with the following channel occupancy pattern:

- Both nodes start with no channel occupancy;
- Every 5 s, the receiver’s channel occupancy increases by 10%, up to 50% channel occupancy.
- After 5 s with 50% channel occupancy, it is reset to 0% channel occupancy for 5 s.
- The sender’s channel occupancy starts increasing following the same pattern.

Figure 3 presents the results of the Synthetic Data test, using UDP traffic, the IEEE 802.11a standard, a fixed rate of 54 Mbit/s, an SNR of 75 dB, a noise floor of -95 dBm, and a channel bandwidth of 20 MHz.

The results obtained using only the InterferencePropagationLossModel (red line) show the impact of the increasing channel occupancy at the receiver, where the Throughput decreases until the 30s mark in simulation time, following the channel occupancy pattern described before. After the 30s mark, the channel occupancy at the receiver is set to 0% until the end of the simulation, which means in this scenario (only the propagation loss model is being used), neither node (A or B) have channel occupancy imposed by other concurrent nodes, so the Throughput is the maximum possible. As seen, the throughput obtained in the simulation (red line) is lower than the expected: at 50% channel occupancy, a 50% throughput was expected, but 33% is observed for the InterferencePropagationLossModel. This is because this model also blocks ACKs coming from the receiver with the same probability as the data frames, triggering more ACK timeouts and re-transmissions at the sender and lowering even further the throughput. This limitation was explained in detail in Section 3.5.
Likewise, when testing the modified MacLow layer (blue line), the Throughput also follows the channel occupancy pattern described for the sender. It starts with no channel occupancy (maximum Throughput) during the first 35 s of simulation. Then, the channel occupancy at the sender increases gradually, resulting in reduced Throughput until the end of the simulation. The modified MacLow is not affected by the same problem of the InterferencePropagationLossModel as 1) packets are blocked before they leave the sender, and 2) the modified MacLow does not affect the transmission of ACKs. Without triggering ACK timeouts or frame retransmissions, the resulting throughput is closer to what is expected.

Finally, results from both models tested together (green line), reproducing the channel occupancy at the sender (modified MacLow) and receiver (InterferencePropagationLossModel), show that for the first 30 s of simulation, where the receiver’s channel occupancy increases gradually, the Throughput decreases accordingly. After this, for 5 s, neither node has channel occupancy, so the Throughput is the maximum possible. For the rest of the simulation, the Throughput decreases gradually with the increase of the sender’s channel occupancy. When reproducing the channel occupancy at the receiver (green line, from 0 to 30 s), the throughput results are affected by the already referred limitation of the InterferencePropagationLossModel.

For comparison, the results obtained using Friis propagation loss model (orange line) are included, which is equivalent to having no channel occupancy, so the Throughput is the maximum possible throughout the simulation.

With this test it was possible to confirm that the new channel occupancy model is able to influence the resulting Throughput according with the channel occupancy experienced by the nodes.

4.2 Controlled Interference Experiment

To further evaluate and validate the proposed channel occupancy model, its operation was also tested using two real experiments executed in the Fed4FIRE+ w-iLab.1 testbed [4]. The objective was to collect traces of channel occupancy during the experiments, representative of the effects of a real communication environment. Those traces were then used in ns-3 to reproduce those past experiments, with the same channel occupancy, using the TS approach. Finally, the throughput results from the TS approach and the real experiments were compared.

4.2.1 Constant Interference Level. This experiment focused on testing the channel occupancy model with a nearly constant level channel occupancy scenario, assessing its effects on the achieved throughput. The experiment was composed of two separate networks, one private network capturing traces of channel occupancy to later reproduce in ns-3 simulations and one interfering network generating interference, each with two nodes communicating using iperf to generate traffic. During the 60 seconds of experiment, the interfering network generated approximately 50% of channel occupancy.

Figure 4 shows the results of this experiment, using the IEEE 802.11a standard, UDP traffic, channel bandwidth of 20 MHz, and both networks using concurrently channel 36.

With approximately 50% channel occupancy caused by the interfering network nodes generating 15 Mbit/s of traffic, the real experiment (blue line) throughput results dropped from 30 Mbit/s to 15 Mbit/s, representing the expected reduction of 50% of throughput. This can also be observed when using the modified MacLow (brown line), where the throughput also drops to approximately 50% of the theoretical values obtained using Friis propagation model (red line). It is important to note that when using only the Friis model we are simulating an interference-free scenario. Similarly, the TraceBasedPropagationLossModel (green line) [7][5] also results in maximum throughput as it only takes into account the SNR traces (which in this case was high enough to max-out the PHY rate of the IEEE 802.11a standard).

As previously stated, the InterferencePropagationLossModel introduces higher losses than the modified MacLow due to its limitation (cf Section 3.5) that result in lower efficiency due to increased ACK timeouts and frame retransmissions. This can be observed in 4 (pink line), where the throughput is lower than the real experiment and the modified MacLow. Furthermore, when using both models (purple line), the throughput is even lower (as expected), confirming what was explained before: without hidden nodes or extra interference at the receiver, only the modified MacLow should be used at the sender, otherwise the resulting channel occupancy in simulation will be higher than the reported by the traces from the real experiment. Finally, in some of the samples it is possible to see that the simulated throughput is much higher that in the real experiments. This is caused by the error of the channel occupancy values reported by the real Wi-Fi cards.

4.2.2 Increasing Interference Level. Now, increasing the complexity of the real scenario, a similar test to the one performed in Section 4.1 – considering increasing channel occupancy along the time – was executed in new experiments.

The test was comprised of two nodes communicating within a private Wi-Fi network (i.e., the experiment we want to reproduce), using iperf generating UDP traffic above link capacity to occupy the available bandwidth, while two interfering nodes were communicating with each other, also using iperf to generate channel occupancy in the private network. The traffic generated by the external nodes introduces channel occupancy on both nodes operating in the private Wi-Fi network as they are all in range of each other (no hidden nodes), and follows a similar pattern as in the previous test with synthetic data.

Figure 4: UDP Throughput Obtained with Controlled Constant Interference from Outside Networks
• Both nodes in our network start with 0% channel occupancy (no iperf traffic from external nodes).
• Channel occupancy on both nodes in our network increases 10% every 5 s up to 50% (iperf traffic from external network increases every 5 s). Because the maximum throughput in this radio link is 30 Mbit/s, each 10% increment of channel occupancy generated by the interfering nodes corresponds to an increase of 3 Mbit/s in the UDP flow generated between the interfering nodes.

The current test was divided into three different experiments, according to the direction of the UDP flow: 1) from node A to node B; 2) from node B to node A; and 3) bidirectional between both nodes. The traces obtained in the real nodes, during the experiment in the testbed, were then used in ns-3 as input to the InterferencePropagationLossModel and modified MacLow, respectively as the traces from the receiver and sender nodes. Traces of SNR were also captured in order to use the TraceBasedPropagationLossModel [6] to use as a baseline for comparison.

![Figure 5: UDP Throughput Obtained with Controlled Interference from External Networks](image)

Figure 5: UDP Throughput Obtained with Controlled Interference from External Networks

For comparison, results obtained using the Friis propagation loss model (red line) and the TraceBasedPropagationLossModel (green line) [7][5] are included and, as shown, are similar as neither model takes into account the channel occupancy, i.e., they simulate a "perfect" communication.

The average Throughput values measured in all the experiments, and their respective simulations counterparts, are presented in Table 1. Note that the simulation using the Friis model produces equivalent results to the TS approach, as we are experimenting with a scenario with ideal link quality, and both models do not reproduce the channel occupancy. The first line (Exp #1) shows the average throughput of the results already presented in Figure 5, while the others represent the other two experiments differing only on the traffic flow directions. Analysing the relative error of the average throughput of each simulation model when compared to the real experiment it is possible to conclude that average throughput is significantly closer to the real experiment, producing more accurate results. Considering the three experiments, on average, the throughput relative error was reduced from 51.12% to 11.83%, which represents a significant improvement over pure simulation (Friis) and Trace-based simulation without channel occupancy reproduction.

5 CONCLUSIONS AND FUTURE WORK

We developed an improved TS approach to reproduce channel occupancy in ns-3 by controlling both the sender and the receiver. At the sender, by manipulating its layer 2 access mechanism, simulating a busy medium; at the receiver, by implementing the InterferencePropagationLossModel, a new propagation loss model to induce packet loss that replicates radio interference from nodes near the receiver that are hidden from the transmitter.

Two tests were performed to evaluate the proposed model. Firstly, by feeding synthetic channel occupancy values to ns-3, which helped validating that the model yielded the expected performance (e.g., with 20% channel occupancy, we would only get about 80% of the expected throughput for the same link quality). Secondly, by using w-iLab.1, a Fed4FIRE+ community testbed, where experiments were performed with real nodes, to assess the model correct operation using real "busy"/channel occupancy traces collected from real experiments.

In w-iLab.1 controlled environment two pairs of nodes were used: one pair representing our network and the second pair representing the concurrent network, which we used to control the amount of induced channel occupancy. Using the TS approach with channel occupancy support we were able to accurately reproduce the throughput of real experiments, lowering the average relative error from 51% to 12%, when compared to the results obtained using pure simulation or the legacy TS approach, which do not account for channel occupancy when reproducing past experiments.

As future work, we will continue to further improve the channel occupancy model in order to support IEEE 802.11n and IEEE 802.11ac. To achieve this, we will study how to modify the InterferencePropagationLossModel so that it does not affect the preamble frame, which, as explained, should not have the same probability of being lost as the rest of the aggregate frame. Furthermore, more...
experimentation is still needed in real world non-controlled scenarios, with random channel occupancy introduced by non-controlled networks. To do this we plan to use the Fed4FIRE+ CityLab testbed, where the nodes are placed around the city of Antwerp, and are subject to an unknown number of interfering networks, with non-controlled channel occupancy.

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REFERENCES

[1] K. Brun, P. Gomes, P. Minet, and T. Watteyne. 2018. Moving Beyond Testbeds? Lessons (We) Learned About Connectivity. IEEE Pervasive Computing 17 (12 2018). https://doi.org/10.1109/MPRV.2018.2873847

[2] R. Campos, T. Oliveira, N. Cruz, A. Matos, and J. M. Almeida. 2016. BLUECOM+: Cost-effective Broadband Communications at Remote Ocean Areas. In OCEANS 2016 - Shanghai. Shanghai, China, 1–6. https://doi.org/10.1109/OCEANSAP.2016.7485532

[3] R. Cruz. 2020. Source Code for the Channel Occupancy Model – use in ns-3.27. http://telecom.inesctec.pt/~hfontes/wns3_channel_occupancy_2020.zip

[4] Fed4FIRE+. 2018. Fed4FIRE+ – The Largest Federation of Testbeds in Europe. https://www.fed4fire.eu/

[5] H. Fontes. 2018. Source Code for the TraceBasedPropagationModel – Use in ns-3.27. http://telecom.inesctec.pt/~hfontes/trace_based_propagation_loss_model2018.zip

[6] H. Fontes, R. Campos, and M. Ricardo. 2017. A Trace-based ns-3 Simulation Approach for Perpetuating Real-World Experiments. In Proceedings of the Workshop on ns-3 (WNS3 17). ACM, Porto, Portugal, 118–124. https://doi.org/10.1145/3067665.3067681

[7] H. Fontes, R. Campos, and M. Ricardo. 2018. Improving the ns-3 TraceBasedPropagationLossModel to Support Multiple Access Wireless Scenarios. In Proceedings of the 10th Workshop on ns-3 (WNS3 18). Association for Computing Machinery, New York, NY, USA, 77–83. https://doi.org/10.1145/3199902.3199912

[8] H. Fontes, V. Lamela, R. Campos, and M. Ricardo. 2019. ns-3 NEXT: Towards a Reference Platform for Offline and Augmented Wireless Networking Experimentation. In Proceedings of the 2019 Workshop on ns-3 (Surathkal, India) (WNS3 ’19). Association for Computing Machinery, New York, NY, USA, 65–72. https://doi.org/10.1145/3321349.3321359

[9] V. Lamela, H. Fontes, T. Oliveira, J. Ruela, M. Ricardo, and R. Campos. 2019. ns-3 NEXT: Towards a Reference Platform for Offline and Augmented Wireless Networking Experimentation. In Proceedings of the 2019 Workshop on ns-3 (Florence, Italy) (WNS3 19). Association for Computing Machinery, New York, NY, USA, 65–72. https://doi.org/10.1145/3321349.3321359

[10] SUNNY. 2018. SUNNY - Smart Unattended Airborne Sensor Network for Detection of Vessels Used for Cross Border Crime and Irregular Entry. http://www.sunnyproject.eu/