

Link-to-System Mapping for 5G NR Sidelink System Simulations

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Abstract—

We describe new packet error models for the Network Simulator version 3 (ns-3) New Radio (NR) sidelink simulation models, derived from an extensive simulation campaign using the National Institute of Standards and Technology (NIST) Fifth Generation (5G) NR Sidelink Link-Level Simulator (LLS). The new error models support the system-level simulation of future 5G sidelink-based public safety scenarios. We first describe the scope, methodology, and output of the link-level campaign and its validation. We next describe the options available to map this data into ns-3 error models, and discuss how we handled various integration issues including interpolation, extrapolation, the need for per-retransmission error tables in ns-3, and how to handle retransmissions with varying signal-to-noise ratio (SNR). Finally, we illustrate the sensitivity of the models to changes in coding, frequency band, numerology, retransmission attempts, and transport block size, and describe our future plans.

Index Terms—NR, Sidelink, Public Safety Communications

I. INTRODUCTION

Future use of Fifth Generation (5G) New Radio (NR) cellular technology in public safety scenarios is expected to leverage sidelink (SL), a mode of operation that allows for user terminals (User Equipment, or UE) to communicate directly with one another, either with the support of a cellular base station (mode 1) or without base station support (mode 2) [1]. Initially, in Third Generation Partnership Project (3GPP) Release 16, the NR SL was specified to support NR Vehicle-to-everything (V2X) services, enabling communication between vehicle-embedded UE and other in-range, authorized UE. Subsequently, Release 17 introduced the specifications for NR Proximity Services (ProSe), for use by both commercial and public safety applications that use the NR SL [2]. Sidelink communications may support first responders in remote off-network locations, tunnels, basements, and other locations where access to a cellular basestation is unavailable. Although SL 3GPP specifications have been developed for many years, commercial availability of SL-enabled 5G equipment is still lacking. As a result, simulation remains a preferred tool for studying the possible performance of such networks.

Network simulation tools are often categorized as “link” or “system” simulators. Link simulators focus on high fidelity modeling of many aspects of the physical layer and communication channels. At this level of granularity, notional

network packets are decomposed into coded and interleaved bitstreams and mapped into notional radio frequency (RF) symbols for transmission over a simulated channel. The RF symbols are possibly subjected to fading channel models (mimicking the signal distortion of multipath channels) and then the receiver processing (synchronization, Doppler effects, quantization, equalization, de-interleaving, decoding, etc.) is modeled. Link simulators are most often used to understand how well an individual link (between a sender and a receiver) will work under complicated impairments, and higher layer protocols and networks of links are usually not modeled. Because these simulators use high-level software languages and general purpose processors to model operations that are typically implemented in custom silicon, the time to simulate a single packet transmission is often orders of magnitude longer than real-world communication time. Some prominent examples of 5G cellular link simulators include MATLAB¹ 5G Toolbox [3] and the Vienna¹ 5G Simulators [4].

System simulators typically do not model the physical layer with high fidelity but instead focus on high fidelity models at the medium access (MAC) layer and above. The Network Simulator version 3 (ns-3) [5] is a prominent example of a 5G-enabled system simulator with a modeling granularity of a transport block (TB). The role of the physical layer model in ns-3 is to use stochastic error models that will lead to TB decoding decisions of either success or failure. Original work on the extension of ns-3 for V2X simulations is reported in [6] and [7]. The description of how SL models developed for V2X simulation have been extended for the performance evaluation of public safety applications, including SL extensions for multi-subchannel operation, multiple logical channel support per UE, dynamic scheduling, and Hybrid Automatic Repeat reQuest (HARQ) feedback, can be found in [8]. The National Institute of Standards and Technology (NIST) also has developed ns-3 models for the ProSe services of Layer-3 UE-to-Network Relay (U2N) and Discovery, and a thorough Mission Critical Push-to-Talk application model.

Although it is technically possible to combine both link

¹Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the NIST, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

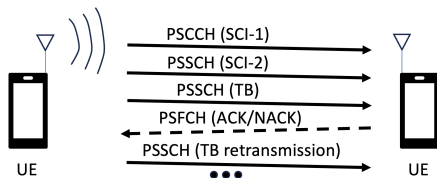


Fig. 1: Example SL message exchange.

and system simulators into a single simulator to achieve high fidelity across the whole protocol stack, such a simulator would run too slowly to be of practical research use. Therefore, many researchers have studied techniques for distilling the results of link simulation campaigns into system-level packet error models. This approach is known generally as “link-to-system mapping” and is the subject of this paper.

In this paper, we describe the generation of ns-3 5G SL error models using link simulation data gathered from a campaign using the NIST 5G NR Sidelink Link-Level Simulator (LLS) [9]. These models improve the fidelity of the ns-3 SL simulated channels to more accurately simulate public safety scenarios. Section 2 describes the main requirements for ns-3 5G SL error models. Section 3 discusses the LLS tool, the modifications made to it, the LLS campaign itself, and how we compared the LLS results against some similar results from the MATLAB’s 5G Toolbox with SL support. Section 4 focuses on the integration of the LLS results with the ns-3 error models. Section 5 describes some sensitivities of the link simulation results in relation to selected configuration parameters. Finally, Section 6 concludes with directions for future work.

II. REQUIREMENTS FOR NS-3

The overall objective is to develop system-level simulation error models to support the message exchange for data transfer illustrated in Figure 1. The figure depicts the transmission of the first stage Sidelink Control Information (SCI-1) over the Physical Sidelink Control Channel (PSCCH), the second stage SCI (SCI-2) over the Physical Sidelink Shared Channel (PSSCH), and the TB, also on the PSSCH. The outcome of a TB decoding attempt may be relayed back to the sender using the Physical Shared Feedback Channel (PSFCH). Depending on the configuration, the sender may send multiple copies of a TB for improved robustness, and may cancel pending retransmissions based on an acknowledgment. For further background on these messages, the tutorial by Garcia et al. is recommended [10]. These messages are encoded and decoded in different ways:

- The PSCCH uses Polar coding and Quadrature Phase Shift Keying (QPSK) modulation;
- The PSSCH SCI-2 uses Polar coding and QPSK modulation at the lowest modulation index;
- PSSCH for TBs uses Low Density Parity Check (LDPC) coding and various modulation;
- TBs may be retransmitted multiple times, and the receiver uses soft-decision decoding to combine multiple receptions. Retransmissions may be sent using either Chase Combining (CC) or Incremental Redundancy (IR) encoding;

- PSFCH carries feedback and uses a specialized Zadoff-Chu coding.

Based on our literature search, no packet-level error models based on Fourth Generation (4G) or 5G sidelink reference channel models are available. ns-3 already has 5G NR SL protocol models at the MAC layer and above, but these models reuse physical layer error models from the uplink (UL) and downlink (DL) channels that are part of the CTTC LENA 5G NR module [11]. 5G SL mode 2 (UE-to-UE) communications links are expected to have different fading channel responses that lead to different error models. This gap motivates our research in this area.

III. LINK-LEVEL SIMULATION CAMPAIGN

In this section, we provide a brief overview of the NIST LLS, the modifications made to it, how we compare its output with similar output from the MATLAB 5G Toolbox, and sample results from the link simulation campaign.

The NIST LLS for 5G SL² is an open source extension to the commercially available Vienna 5G Simulators. These simulators rely on MATLAB for some signal processing and 5G signal decoding methods. The NIST LLS version used herein makes the following changes to the previously released version:

- Channel Quality Indicator (CQI) tables (0..15) are replaced by Modulation and Coding System (MCS) tables (0..28), allowing the MCS value to be directly configured;
- the center frequency is set to 793 MHz (public safety band n14);
- the number of physical resource blocks (PRBs) is changed from 52 to 10, for one subchannel operation;
- the number of frames to simulate per sweep value is changed from 10 000 to 40 000;
- the block error ratio (BLER) granularity is changed from 10^{-3} to 10^{-4} .

The program `main_adaptive_SL_batch.m` runs an adaptive sweep of path loss values to find, from among a possibly wide range of input path loss values, those path loss values that provide BLER values between 0 and 1. Typically, 10 to 20 tuples of (SNR, BLER) are produced for each parameter combination of interest (MCS, channel profile, numerology, number of transmissions, etc.).

For each path loss value selected in the adaptive sweep, 40 000 frames were simulated. The term “frame” is a slight misnomer in this context; it is a SL slot containing one notional TB that fully occupies the configured number of PRBs. That is, the TB size is not directly configured but instead inferred from the number of PRBs, the MCS value, the number of PSSCH symbols in a slot, and the multiple input multiple output (MIMO) dimension. The number of TBs sent per data point is determined by the number of transmissions configured for each TB. If, for example, one transmission per TB is configured, 40 000 different TBs will be sent (in consecutive

²<https://www.nist.gov/services-resources/software/new-radio-sidelink-simulator>

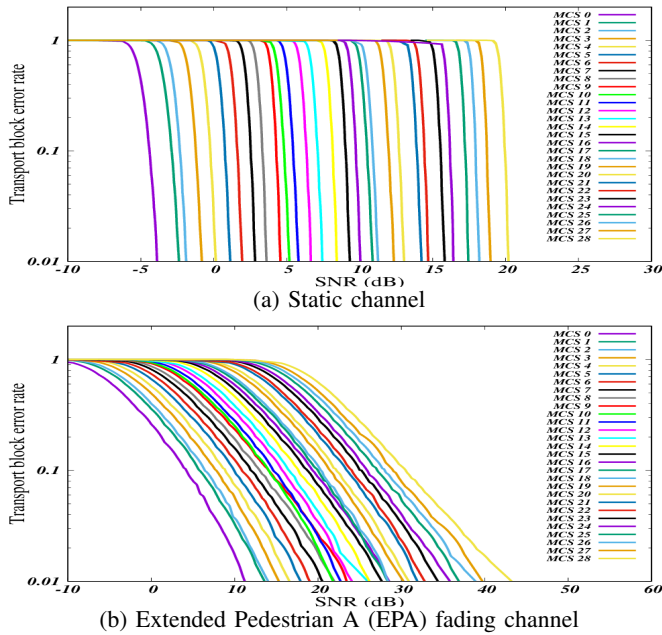


Fig. 2: NIST LLS results with numerology 0, NumTx=1.

slots), a different channel realization will be drawn for each, and the simulator will attempt to decode and count each TB as successful or errored. After 40 000 frame transmissions, the TB BLER will be calculated for that SNR point. If, however, five transmissions are configured for each TB, there will be $40000/5 = 8000$ TBs sent, and the simulator will perform soft-decision decoding on the multiple transmissions, and BLER output will then correspond to the final error rate after up to five transmissions were transmitted.

After the NIST LLS was released, MATLAB released SL support for their 5G Toolbox. We wanted to confirm that the definition of SNR was consistent across both tools, and that both tools provided comparable BLER curves for similar configurations. We have been able to adapt a MATLAB-provided example program to use a static (Additive White Gaussian Noise (AWGN)) channel at three MCS values (4, 11, 17) and either 10 PRBs or 20 PRBs, and confirmed that the BLER values are within about 1 dB of SNR for both simulators.

According to the above, we carry out a link simulation campaign by varying the following parameters:

- MCS values 0 through 28;
- Static and Extended Pedestrian A (EPA) channel;
- Numerology 0 for static channel, and both 0 and 1 for EPA channel;
- Maximum number of transmissions per TB from 1-5.

The EPA channel is a multipath channel profile defined by 3GPP for LTE [12] and is one of a few available channel models applicable to device-to-device communications within the Vienna link simulator.

In the LLS simulator, the first stage control information is always received successfully, and the second stage control information (SCI-2) can be configured to be error-free or

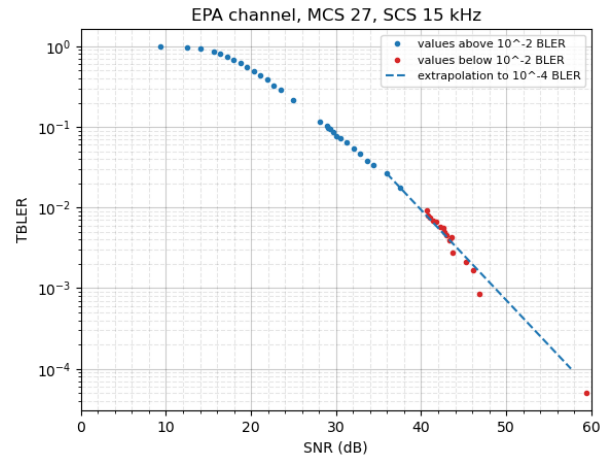


Fig. 3: Extrapolation below BLER of 10^{-2} .

evaluated with an error model; we used the latter setting for this campaign. Therefore, each TB reception follows two checks: the SCI-2 must be considered error-free for the TB to be added to the decoding buffer, and then the TB error model is consulted to determine whether a reception has occurred.

The LLS does not directly support the setting of the TB size, but instead allows configuration of the number of physical resource blocks (PRBs), and the TB size is inferred as the maximally sized TB that fits within the number of PRBs. In this campaign, we set the number of PRBs to 10, corresponding to one subchannel in frequency.

Figure 2a shows a sample of the LLS output plotted for MCS values 0 to 28, for the static channel, using Numerology 0, and one transmission. Figure 2b illustrates the more gradual slope of the BLER curves over a range of SNR values, due to the EPA fading model. Different fading channel models will have different slopes and breakpoints, but the EPA channel results are representative of the difference in performance compared to that of the static channel.

IV. ADAPTATION TO NS-3

Adapting the LLS data to ns-3 requires design decisions on whether to transform or compress the LLS data, and on how to use the aggregate statistics compiled by the LLS into per-retransmission statistics needed by ns-3.

The LLS data provides BLER values for discrete values of SNR, but ns-3 propagation models can generate a continuous range of SNR. Moreover, retransmissions may be received with different SNR values. We describe below how the new ns-3 models handle these issues.

A. Link-to-system mapping

As introduced above, the set of LLS data for each run consists of roughly 10 to 20 tuples of (SNR, BLER) values for each parameter combination of interest (MCS, channel profile, numerology, and number of transmissions). These must be transformed to provide a continuous function of SNR-to-BLER for use in ns-3. There are a few possible techniques:

- 1) Directly import the data points and use piecewise linear interpolation;

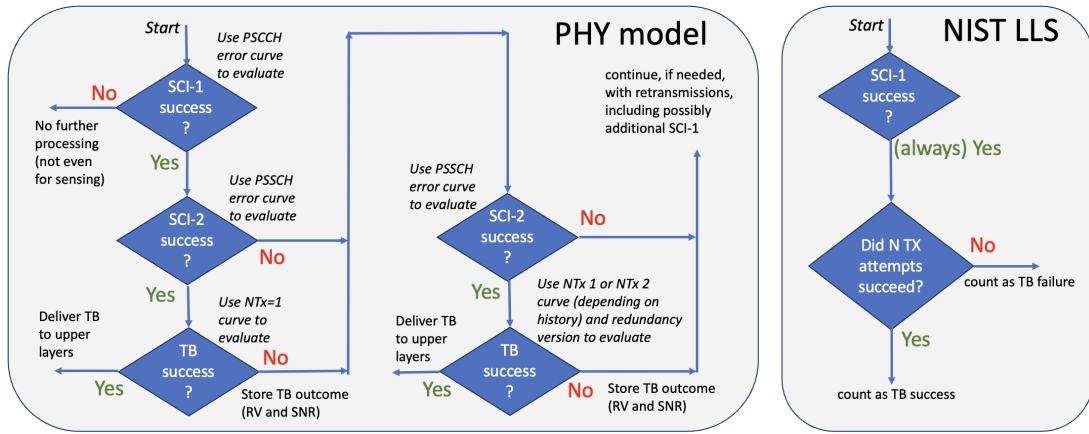


Fig. 4: Difference between the modeling of reception events and the statistics collected by NIST LLS.

- 2) Perform polynomial curve fitting (such as available in tools such as MATLAB) and store the coefficients;
- 3) Perform a link-to-system mapping that transforms the ns-3 SNR into an “effective SNR” that maps to the set of static channel curves (imported as piecewise linear), and store the mapping function coefficients.

Curve fitting approaches can reduce the data storage requirements vs. storing all of the raw data points. Many techniques are studied in the literature, including Effective Exponential SINR Metric (EESM), Mutual Information-based Effective SINR Metric (MIESM), Rate-based Information Rate (RBIR), and EESM Logarithmic Skew-Generalized Normal (EESM Log-SGN) [13]. However, any such mappings will introduce some divergence with the underlying data, and some type of goodness-of-fit evaluation should be conducted. Additionally, the storage of the raw 10 to 20 tuples per curve is on the order of storage requirements of some of the higher-order curve fitting techniques like EESM Log-SGN. Therefore, we directly import the NIST LLS curve data into the ns-3 C++ implementation, and linearly interpolate as needed.

Storing a set of (BLER, SNR) tuples does not solve the ns-3 simulation case for determining the BLER of a SNR point that is not in the data set. For this situation, we implement a basic linear interpolation between the points bounding the desired SNR to obtain an interpolated BLER.

There is a practical need to limit the number of simulation trials of a given configuration, but the probability estimators for rare events will be unreliable. Determining the limit is commonly known as the stopping problem for Monte Carlo simulations [14]. For 40 000 trials, narrow confidence intervals around the sample means are achievable down to a BLER of 10^{-2} but below that BLER, the data points become more sparse and the slope of the curve becomes more variable, as illustrated in Figure 3, in which the red data points indicate the less reliable data. This TBLEP threshold could be lowered but at the cost of more simulation trials. There are a few choices for how to estimate the BLER values in the SNR region where there is more variability in the data. One possibility is to truncate the curve and have the BLER fall to zero above the

SNR corresponding to the target threshold (in this case, 10^{-2}), but this approach does not match real channels very well since higher-layer protocols should be exposed to some less frequent error events. Another possibility is to perform a curve fitting to the available data, possibly by also removing the values below 10^{-2} , and extrapolate that curve to higher SNR. A third possibility is to note that on this logarithmic scale, the curve has a roughly linear slope in the region of interest, and to therefore extend a line formed by the last two points located above the BLER threshold of 10^{-2} to extrapolate to higher SNR (lower BLER) values. We adopt the third approach (as depicted in Figure 3, and this extrapolation has been applied to the LLS campaign data, down to a configurable lower BLER threshold of 10^{-4}).

ns-3 must also handle cases in which different transmissions arrive with different SNRs. This case does not arise in the link simulation data because mobility and interference are not modeled. In the current ns-3 model, we have adopted the approach of averaging the SNR values (expressed as a linear ratio) and use that average as an “effective SNR” for BLER lookup. A past technical report from NIST [15] employs a more sophisticated approach to handle this case, but we adopted linear averaging due to the lack of physical justification and validation for the alternative.

B. Per-retransmission statistics

When retransmissions are being used, ns-3 needs to evaluate TB success or failure upon each retransmission attempt, in order to pass successfully decoded TBs to higher layers at the right times. The permutations of possible events to model get very large as the number of retransmissions increase. The left side of Figure 4 illustrates the flow of possible error model evaluations and outcomes for the scenario of a TB transmitted two times. The conceptual physical layer (PHY) model would evaluate the SCI-1, SCI-2, and the TB, and if the TB is not decoded successfully, store the history of the decisions for later use in the evaluation of the retransmission. For example, whether the SCI-2 is decoded successfully or not in the first attempt has bearing on the probability of decoding the TB

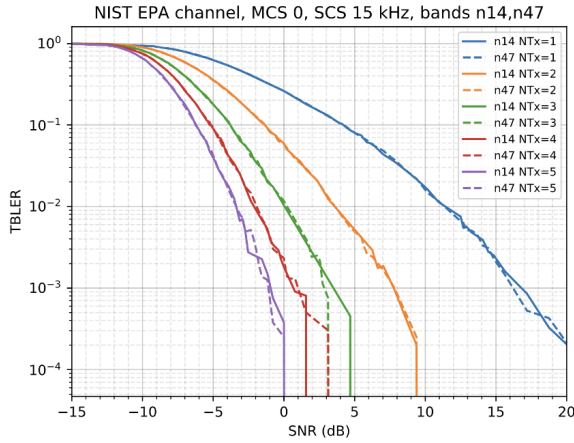


Fig. 5: Sensitivity of EPA channel to central frequency and retransmissions.

successfully in the second attempt, because the soft decoding buffer will have data from either one or two transmissions. However, the NIST LLS does not separately count all of these outcomes, but instead calculates the overall success at the end of the sequence of TB attempts. Furthermore, the SCI-1 is assumed to be error-free in the NIST LLS. This difference is illustrated by Figure 4.

Despite this mismatch, we make use of conditional probability to approximate the probabilities needed by ns-3 using the probabilities tabulated by the NIST LLS. In ns-3, we disable the separate evaluation of SCI-2 to match the NIST LLS setup, since in the NIST LLS the effect of SCI-2 decoding is captured by the probabilities being recorded for overall TB success or failure. The evaluation of importance for ns-3 is the event that the current TB transmission is successfully decoded. This event is conditional on the history of past decoding events. However, the NIST LLS tabulates the unconditional probability of a success after k tries. This leads to the following.

For $i = 1, 2, \dots, n$, let E_i be the event that the i -th transmission is in error. From link-level simulation, the probability of error after n transmissions is the probability that none of the n transmissions and decoding attempts are successful. That is,

$$Pr(error)_{(n \text{ transmissions})} = Pr(E_1, E_2, \dots, E_n).$$

The conditional probability that the n th transmission is in error given the previous $n - 1$ transmissions are in error, is $Pr(E_n|E_1, E_2, \dots, E_{n-1})$.

Hence, from Bayes' Theorem:

$$\begin{aligned} Pr(E_n|E_1, E_2, \dots, E_{n-1}) &= \\ Pr(E_1, E_2, \dots, E_{n-1}, E_n) / Pr(E_1, E_2, \dots, E_{n-1}). \end{aligned}$$

We therefore store the unconditional probabilities collected by the NIST LLS in ns-3, and obtain the desired conditional probability by taking the quotient in the above equation.

We confirmed that this approach yields performance that matches the NIST LLS data by writing an ns-3 program to sweep the SNR for each configuration, and for each SNR

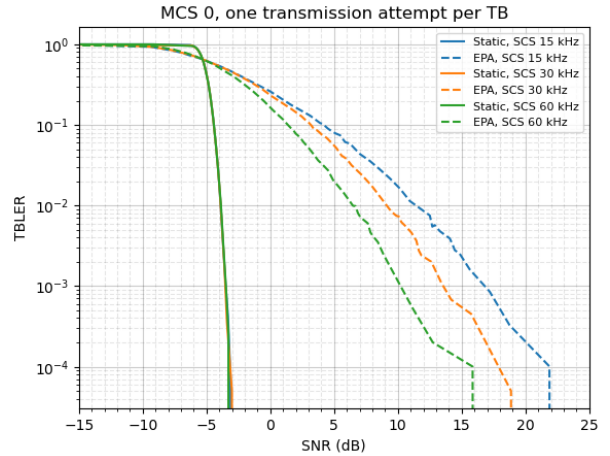


Fig. 6: Sensitivity to numerology for static and EPA channels.

value, sending 40 000 UDP packets and calculating the resulting packet loss ratio at the application layer of the receiver. This end-to-end packet loss ratio aligned with the NIST LLS BLER results, as expected.

V. SENSITIVITIES

The NIST LLS campaign provides insight into the sensitivities of various parameters to the error model outcomes. Some of these sensitivities are well known due to previous works; for instance, that the BLER is highly sensitive to the MCS (e.g., [11]). When the BLER is very sensitive to a parameter, and in an unpredictable way, the LLS campaign must typically be extended in another dimension according to that parameter. This leads to a combinatorial growth in the number of link simulations and tables. Therefore, where good approximations can be used to avoid the increasing dimensionality of the error model data, such approximations should be considered. Below we illustrate the sensitivity of the results to some selected simulation parameters.

A. Frequency and number of retransmissions

Figure 5 shows the LLS results from a configuration with the EPA channel, numerology 0, MCS 0, and two different bands: band n14 (public safety) and band n47 (V2X). Although the carrier frequency strongly affects path loss, the SNR values are calculated after path loss has been accounted for, and the results illustrate that the frequency band does not affect the aggregate fading performance. This figure also illustrates the strong dependence of the BLER on the number of transmissions attempted. When a TB is retransmitted, not only is there another opportunity to decode due to a different channel realization, but also the impact of soft decision decoding is that successive attempts will usually increase the probability of decoding. Up to five transmission attempts are plotted in Figure 5, and a general trend of diminishing improvement with each additional transmission attempt is visible. However, the performance continues to improve with additional retransmissions beyond four. Our current simulation campaign did not generate statistics for higher numbers of transmissions, because there are expected to be fewer demands

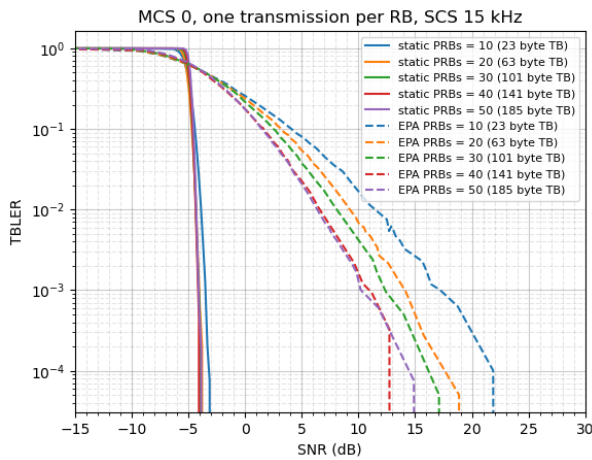


Fig. 7: Sensitivity to transport block (TB) size.

for having this data available in ns-3 simulations, considering that more than five transmissions of a TB is not as likely in operational networks due to channel efficiency or latency considerations. The ns-3 simulator is configured to use the data corresponding to the most transmission attempts if a case arises in which decoding of more attempts is needed.

B. Numerology

The use of increased subcarrier spacing (higher numerologies) is possible in 5G NR to compensate for multipath, but is not likely to improve static channel performance. This expected result is evident in the data shown in Figure 6, in which three different subcarrier spacings (15, 30, and 60 kHz) are used on static and EPA fading channel. The static channel results show insensitivity to numerology, and so for this reason, we only conducted a simulation campaign for a single numerology for static channels, but used two numerologies when using the EPA channel. Sidelink mode 2 operation in band n14 is not permitted to use more than two numerologies.

C. Transport block size

The NIST LLS simulator allows one to configure the number of PRBs used, in increments of 10 PRBs. For sidelink channels in band n14 with numerology 0, the maximum size is 50 PRBs. The data in Figure 7 shows that the performance in fading channels varies as a function of TB size. Our NIST LLS campaign configured 10 PRBs. Our next planned task is to run a campaign with different TB sizes and then evaluate whether this is another dimension to be added to the ns-3 error model tables (with another dimension of interpolation to account for TB sizes between the values simulated by the NIST LLS) or whether some approximate offset from a single TB value can be consistently used across the various configurations. This is a topic for further study.

VI. CONCLUSION

This paper reports on new SL error models for a multipath channel model of relevance to future public safety networks, for use in the ns-3 network simulator. The error models have been obtained from the NIST LLS and the data has

been integrated into ns-3 error model tables. The focus has been on extending the ns-3 simulation capability for SL mode 2 (device-to-device) operation expected for future public safety scenarios in band n14. We believe this to be the first publication of a link-to-system mapping campaign for 5G NR SL channel models. The source code and scripts for both the link-level simulator and for the ns-3 5G NR SL model are in the process of public release, and the approach will be extensible by future users to other channel models and parameter configurations.

We next plan to extend the link simulation campaign to study multiple TB sizes. Other parameters could be explored further, such as MIMO configurations, or the difference in performance between CC and IR for retransmissions, to determine suitable approximations at the ns-3 level (or additional error model curves). We expect that the new error models will enable more realistic ns-3 performance studies for which the higher-layer protocols must compensate for challenging fading multipath environments.

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