Efficient PHY Layer Abstraction for 5G NR Sidelink in ns-3

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Overview

- 5G NR Sidelink (SL) Link level Simulator (LLS) Recap
- PHY Layer Abstraction for 5G SL
- Simulation Results
- Conclusions and Future Work

5G NR Sidelink LLS Recap

- First publicly accessible 5G NR link-level simulator developed by NIST [1];
  - Matlab-based;
  - Current release focus on
    - Point-to-point NR SL;
    - Data transmission (PSSCH);
  - Inherited partial PHY modules from the existing LLSs
    - Vienna UL/DL LLS [2];
    - MathWorks 5G toolbox [3];
  - Developed specific NR SL features.

Table 1: Supported Features by NIST NR SL Simulator

Inherited features	Developed features
General Functionality	SL BWP and resource pool
Channel Coding	SL slot format
Channel Models	Data and control multiplexing
Channel Estimation	Data and SCI2 scrambling
Modulation	SL layer mapping and precoding
Equalization and Detection	error-free and error-prone SCI2
	Blind- and feedback-based HARQ
	Pathloss-to-range conversion

[1] Peng Liu, Chen Shen, Chunmei Liu, Fernando J Cintrón, Lyutianyang Zhang, Liu Cao, Richard Rouil, and Sumit Roy. 5G New Radio Sidelink Link-Level Simulator and Performance Analysis. In Proceedings of the 25th International ACM Conference on Modeling Analysis and Simulation of Wireless and Mobile Systems, pages 75–84,
[2] Stefan Pratschner, Bashar Tahir, Ljiljana Marijanovic, Mariam Mussbah, Kiril Kirev, Ronald Nissel, Stefan Schwarz, and Markus Rupp. 2018. Versatile mobile communications simulation: the Vienna 5G Link Level Simulator. EURASIP Journal on Wireless Communications and Networking 2018, 1 (20 Sept. 2018), 226.
[3] The MathWorks Inc. 2022. 5G Toolbox User's Guide. https://www.mathworks. com/help/pdf_doc/5g/5g_ug.pdf

PHY Layer Abstraction for 5G NR SL – Motivation

- Hour-long runtimes for NR SL link simulations ;
  - Inefficient and impractical for system-level simulations in ns-3;
- Different link-level performance between SL and UL/DL;
  - Available NR UL/DL PHY layer abstraction [4], but no available SL PHY layer abstraction!
  - The first publicly accessible NR SL LLS was recently developed.

Table 2: Runtimes for 40000-TB Simulation at One SNR Point using NIST 5G NR SL Simulator

$n_t \times n_r$	Numerology	# of RBs	Full PHY
1×1	0	10	48 min
1×1	0	20	56 min
1×1	1	10	57 min
1×1	1	20	62 min
2×2	0	10	89 min
2×2	0	20	108 min
2×2	1	10	111 min
2×2	1	20	156 min

[4] Sandra Lagen, Kevin Wanuga, Hussain Elkotby, Sanjay Goyal, Natale Patriciello, and Lorenza Giupponi. New Radio Physical Layer Abstraction for System-level Simulations of 5G Networks. In 2020 IEEE International Conference on Communications (ICC), pages 1–7, Dublin, Ireland, 2020

PHY Layer Abstraction for 5G NR SL – Contribution

- Set initial goal for NR SL PHY layer abstraction in ns-3
  - Deploy and validate the EESM-log-SGN method [5] for the channel model in the current release of SL LLS simulator;
    - EESM-log-SGN deals with I.I.D. channel instances.
  - Future PHY abstraction work will target temporal channel variations.
    - UE mobility must be considered in SL.

[5] Sian Jin, Sumit Roy, and Thomas R Henderson. Efficient PHY Layer Abstraction for Fast Simulations in Complex System Environments. IEEE Transactions on Communications, 69(8):5649–5660, 2021.

PHY Layer Abstraction for 5G NR SL - Scenario

- SISO + Single transmission;
- I.I.D. channel instances
  - Invariant channel during each TB transmission over a slot;
  - Different TBs have different channel instances.

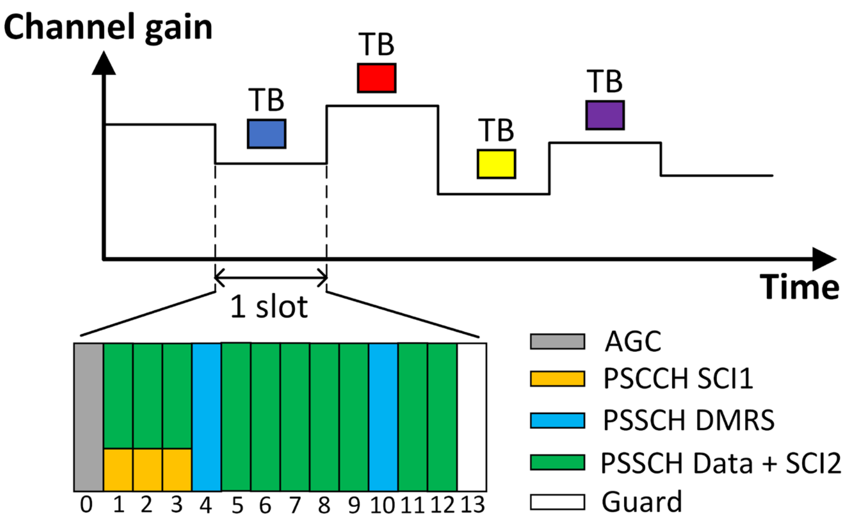

Figure 1: Frequency-selective Block Fading Channel in the NIST 5G NR SL Simulator

PHY Layer Abstraction for 5G NR SL – Implementation Flow Chart

- **PHY layer abstraction**: Packet error model that produces a decision on whether the packet is successfully received based on the PHY layer setup.
- **Offline link simulation + Online network simulation**

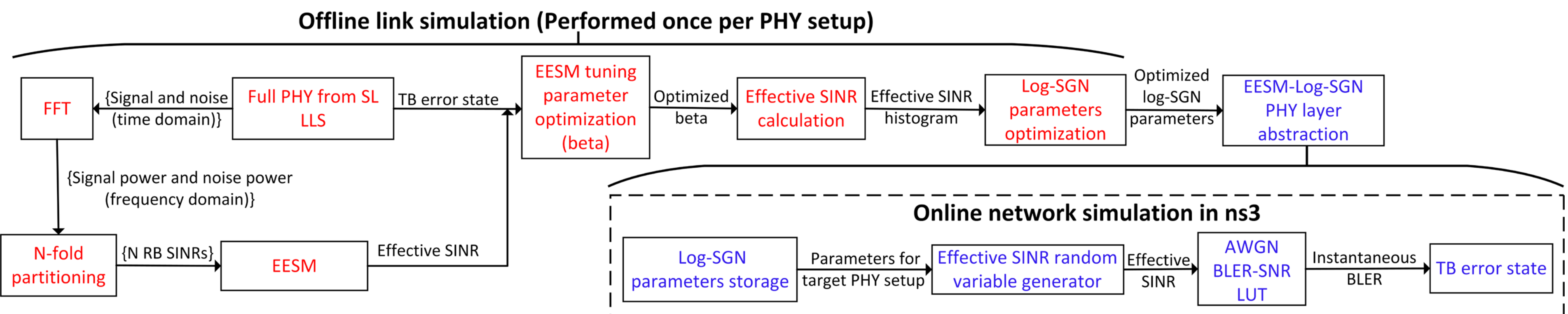

Figure 2: Flowchart of Implementing the PHY Layer Abstraction for 5G NR SL

PHY Layer Abstraction for 5G NR SL – Offline Link Simulation

- **Step 1:** Running full PHY (e.g., 6 SNR points, 40000 TBs at each SNR point) for a specific PHY setup, obtain:
  - Each TB error state: 0/1 representation;
  - N-RB SINR of each TB → EESM(β, N-RB SINR) → Effective SINR of each TB.
- **Step 2:** Optimizing EESM tuning parameter - β
  - Minimize the MSE between BLER-SNR under the AWGN channel and simulated BLER-effective SINR under the fading channel;
  - Optimized effective SINR histogram for each SNR point.
- **Step 3:** Optimizing log-SGN parameters → EESM-log-SGN PHY abstraction
  - Effective SINR histogram is fitted by 4-parameter log-SGN distribution.

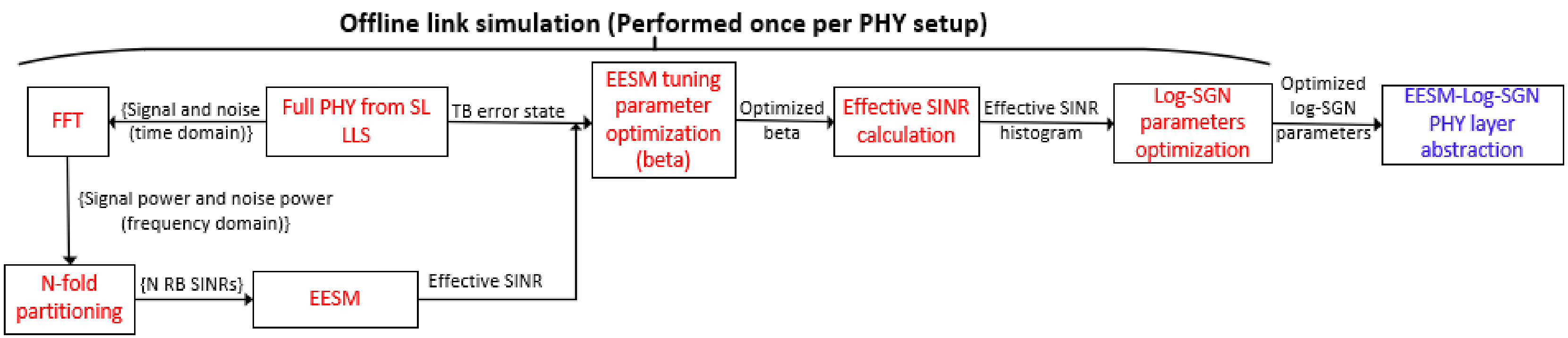

Figure 3: Flowchart of Offline Link Simulation

PHY Layer Abstraction for 5G NR SL – Online Network Simulation

- **Step 1**: Choose log-SGN parameters;
- **Step 2**: Generate X from the random variable generator → Effective SINR = $\exp(X)$;
- **Step 3**: Find the BLER based on the BLER-SNR lookup table under the AWGN channel → One TB error state;
- **Step 4**: Repeat Step 2 - 3 for more realizations.

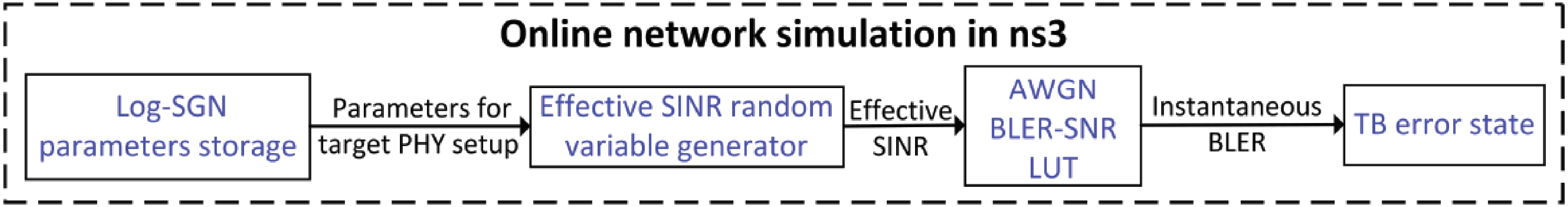

Figure 4: Flowchart of Online Network Simulation in ns-3

Simulation Results - Setup

- Perfect PSCCH (SCI 1);
- Unicast: Point-to-point NR SL.

Table 3: Main PHY Layer Setup

Communication system	5G NR SL
Link simulator	NIST 5G NR SL link simulator
Number of realizations at each SNR	40000
Channel model	Pedestrian-B [19]
Channel coding	LDPC
Number of RBs	10
CQI (MCS)	6 (8)
Numerology	0
SNR points	{2.0, 4.4, 6.8, 9.2, 11.6, 14.0, 16.4}
Channel estimation error	Noise-free
CPU	Intel Core i7 CPU at 2.60GHz

Simulation Results - Validation

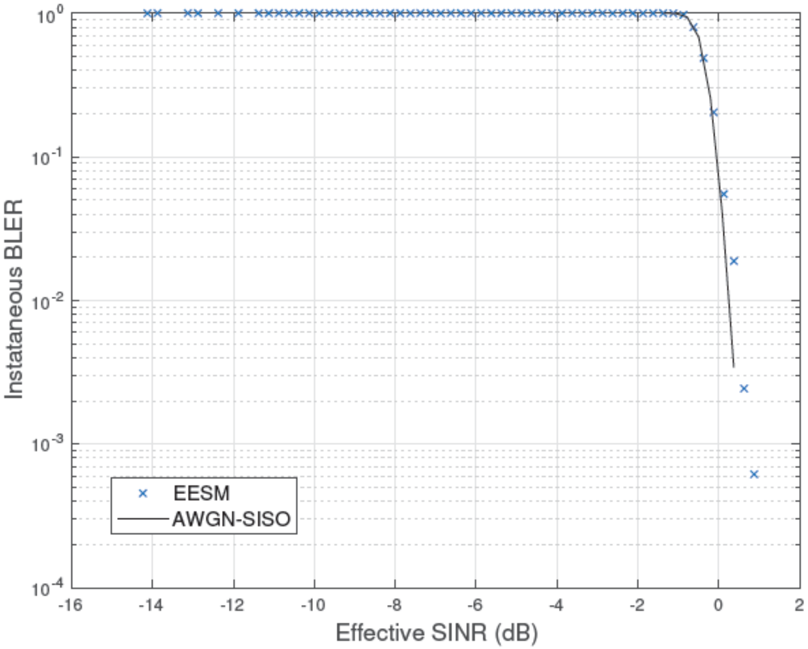

Figure 5: Validation of EESM β Calibration

Optimal β = 0.5988

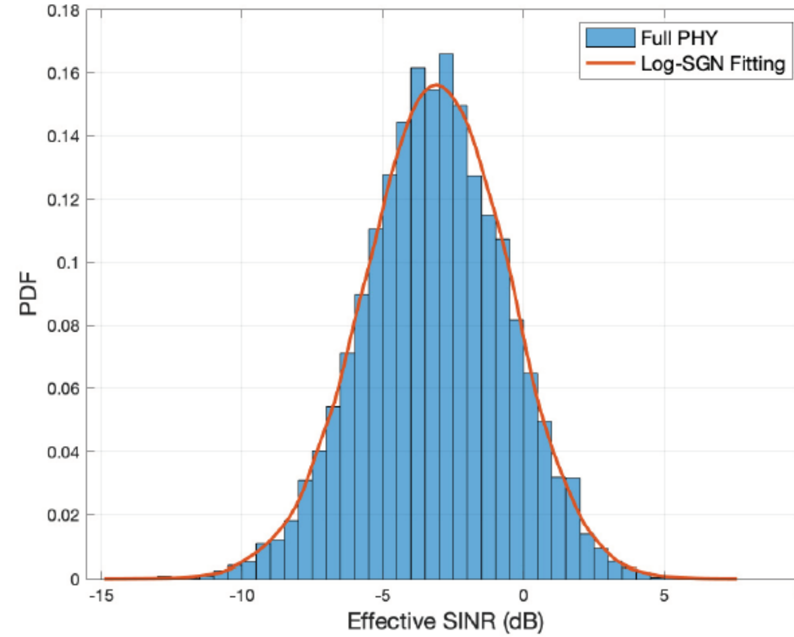

Figure 6: Effective SINR Histogram under SNR = 2

SGN(-0.9403, 0.6194, 0.5727, 0.1661)

Table 4: Log-SGN Table with CQI 6 (MCS 8)

SNR	$\hat{\mu}$	$\hat{\sigma}$	$\hat{\lambda}_1$	$\hat{\lambda}_2$
2.0	-0.9403	0.6194	0.5727	0.1661
4.4	-0.6545	0.6634	0.9407	0.0939
6.8	-0.3791	0.7273	1.5644	0.3165
9.2	-0.1116	0.8029	2.2530	0.5263
11.6	0.1107	0.9158	3.0635	0.7346
14.0	0.3597	1.0294	3.4050	0.4942
16.4	0.6855	1.1506	3.0456	0.0022

- 7 SNR points in the full PHY → 7 effective SINR histograms → 7 log-SGN distributions → 7 pairs of log-SGN parameters

Simulation Results - Validation

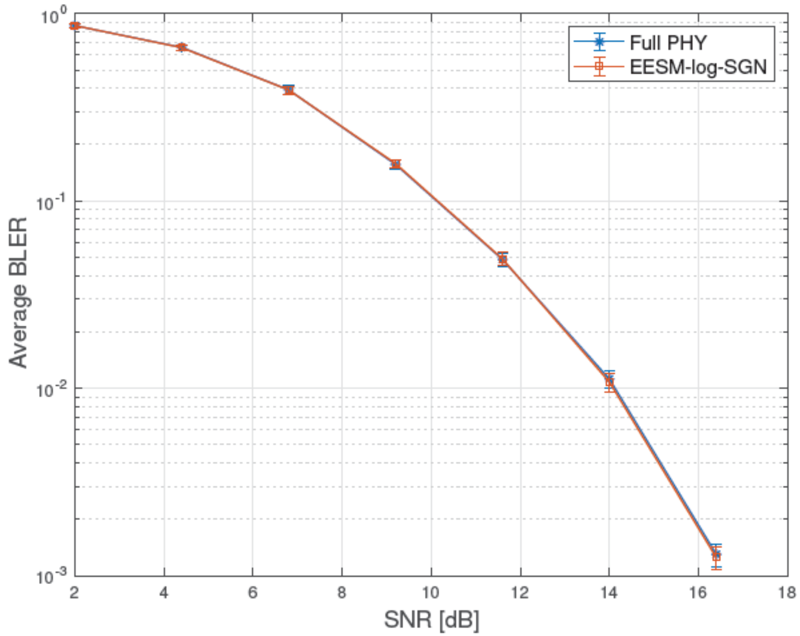

Figure 7: Cross Validation regarding the Average TB BLER

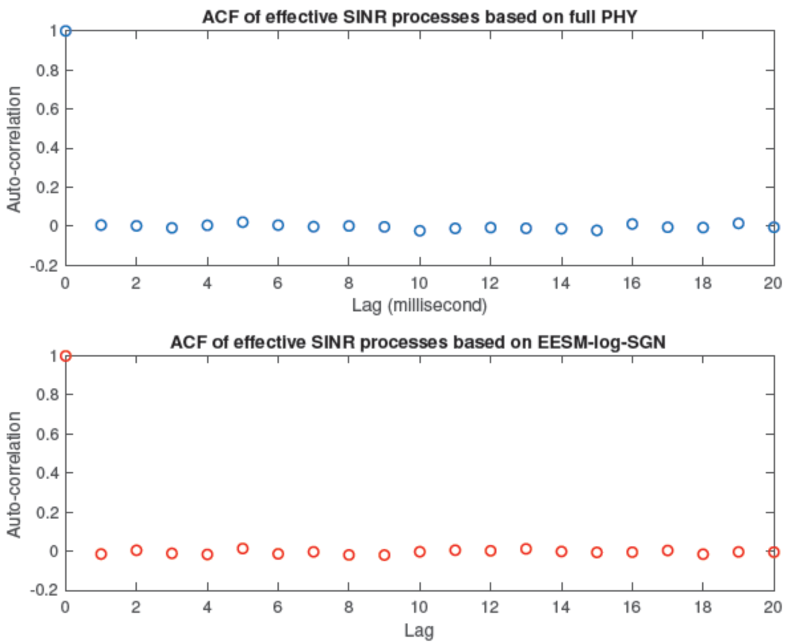

Figure 8: Cross Validation regarding the Possible Temporal Correlation: ACF of Effective SINR Processes under SNR = 2.0

- Average TB BLER at each SNR point is validated;
- Possible temporal channel correlation is validated;
  - No temporal correlation among channel instances in the currently supported full PHY simulations.

Simulation Results - Validation

Table 5: Average Runtimes at One SNR Point over 10 Trials

# of TBs	Numerology	# of RBs	EESM-log-SGN
40000	0	10	0.6 sec
40000	0	20	0.6 sec
40000	1	10	0.6 sec
40000	1	20	0.6 sec
80000	0	10	1.2 sec
80000	0	20	1.2 sec
80000	1	10	1.2 sec
80000	1	20	1.2 sec

- Average runtimes are reduced significantly;
  - Only sensitive to # of TB;
- Different impact of numerology on optimal β between NR UL/DL and SL.

Figure 9: Optimal β under Different MCS and Numerology in NR UL/DL [4]

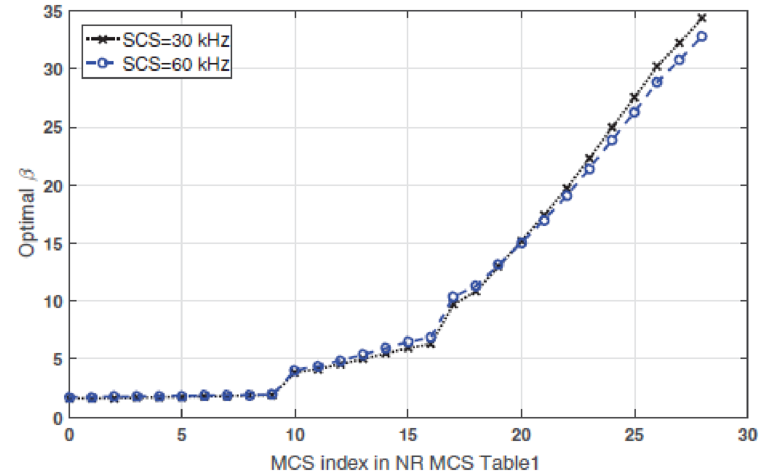

Table 6: Optimal β under Different MCS and Numerology in NR SL

CQI (MCS)	$\mu = 0$	$\mu = 1$
1 (0)	0.5527	0.8360
2 (0)	0.5632	0.9242
3 (2)	0.5578	0.8642
4 (4)	0.5747	0.9125
5 (6)	0.6033	1.0043
6 (8)	0.5988	1.0952
7 (11)	0.9286	1.8323
8 (13)	1.8635	3.1353
9 (15)	3.0324	5.2644
10 (18)	4.3438	7.3591
11 (20)	5.9274	10.4613
12 (22)	8.0815	14.1499
13 (24)	9.5974	18.0639
14 (26)	11.625	24.2971

Conclusions & Future Work

- **Conclusion**
  - Good accuracy in modeling the 5G NR SL PHY performance with EESM-log-SGN method;
  - Significantly reduced runtimes;
  - Different impact of numerology on optimal β between NR UL/DL and SL.

Conclusions & Future Work

- **Future Work**
  - Incorporating time-varying channels (temporal channel correlation);
  - Incorporating multiple TB re-transmissions (HARQ case);
  - Extending the NR SL PHY abstraction to multiple streams (maximum number can be up to 2).