Multi-Network WiFi Analysis & Optimization via ns-3

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Wireless Network Simulation with ns-3: Status & Objectives

❖ **Cross-layer simulation Complexity & Scale**

❑ Inherent complexity: Larger channel BWs, MIMO, Beamforming
non-AWGN (fading …) channels

→ better PHY abstractions for network simulations

❑ Scale: multi-cell simulations (dense, overlapping)
- inter-cell interactions (MU transmissions)

→ confront exploding state-space dimensionality

ns-3 model Trade-offs: Simulation run-time (complexity)
vs Accuracy !

❖ **Rapid Evolution of Wireless Standards/Design features**

→ always in catch-up, needs more global collaboration to sustain

Outline

- **WiFi Models in ns-3: Summary of Recent Advances**
  - ☐ .11 PHY Abstractions for ns-3 WiFi network simulations
    - offline but computationally exhaustive
      → need for Fast Link-2-System (L2S) mappings
  - ☐ mult-BSS WiFi simulation
    - complexity due to network interactions (dense, overlapping home/enterprise networks)
      → need to benchmark for future scaling of simulations

Ns-3 WiFi Working Group: Update on 802.11ax & .be models

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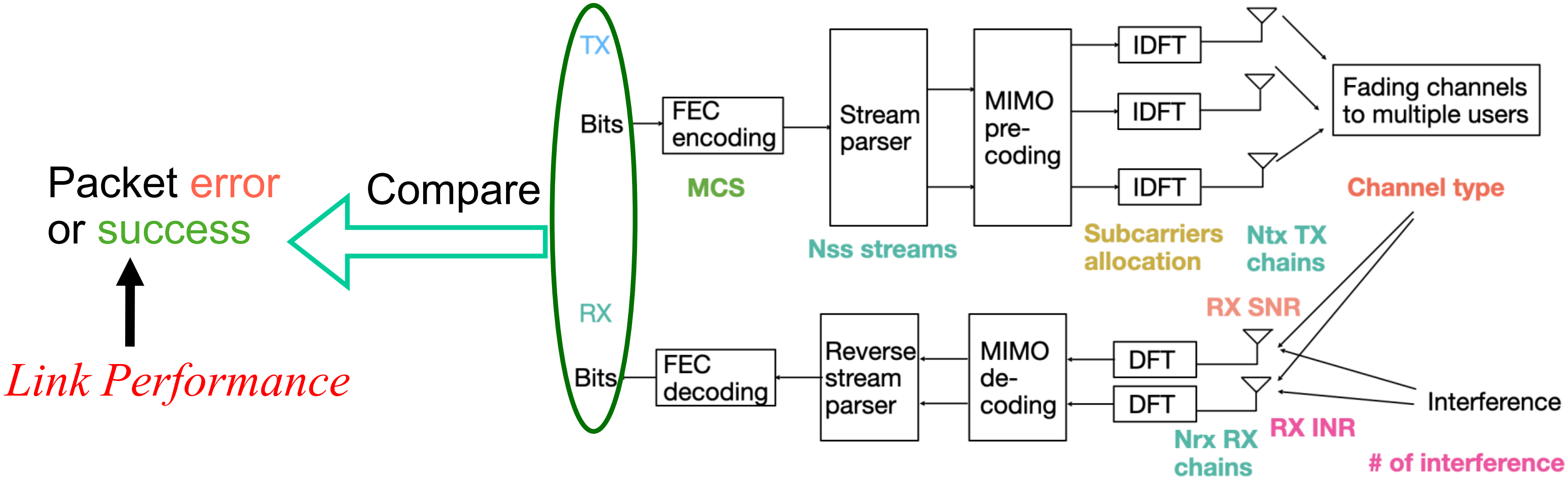
PHY abstraction for Network Simulation ?

- **PHY Simulation: produce packet error rate (PER) as a function of**

Channel type MCS Subcarriers allocation MIMO dimension RX SNR RX INR

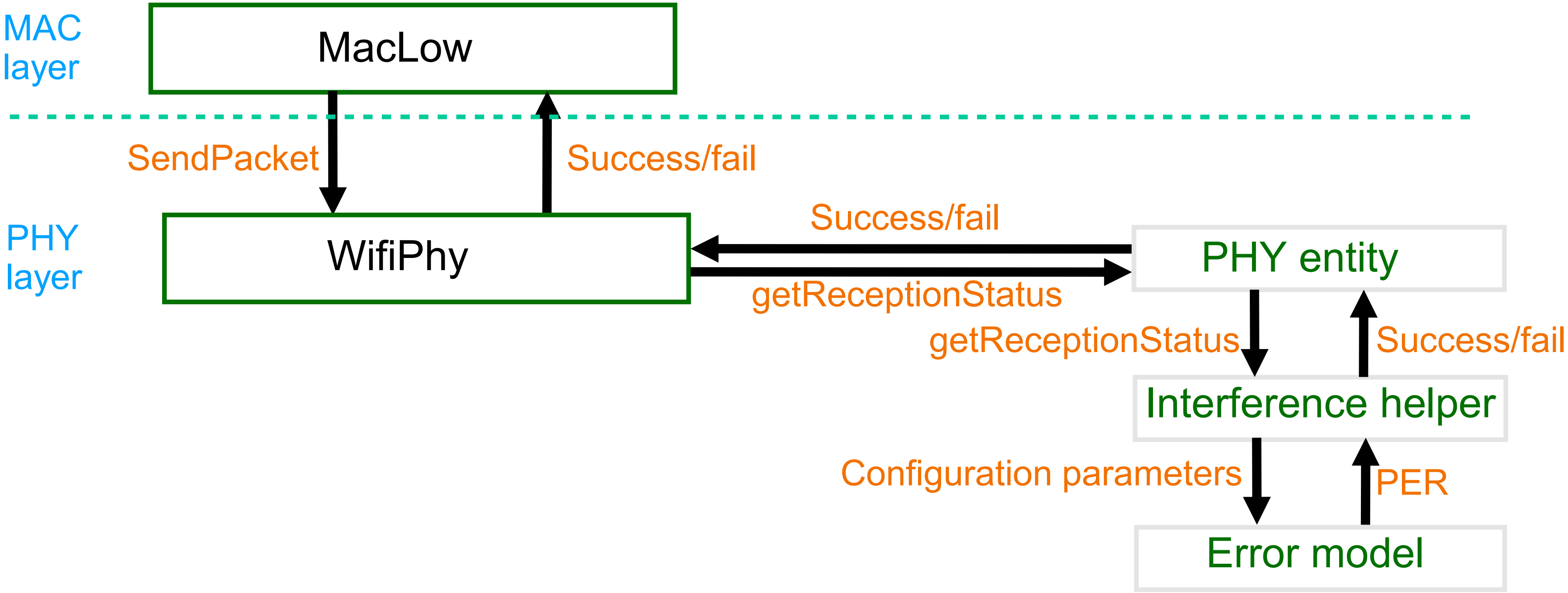


Full PHY simulation block diagram

PHY Abstraction for Network Sims: PER as a function of *effective* SINR

effective SINR: single value @ Rx output over all sub-carriers/streams, maps link performance over specific channel to link PER over AWGN.

PHY abstraction for ns-3 : L2 Performance Evaluation



MAC layer

MacLow

SendPacket

Success/fail

PHY layer

WifiPhy

Success/fail

getReceptionStatus

PHY entity

getReceptionStatus

Success/fail

Interference helper

Configuration parameters

PER

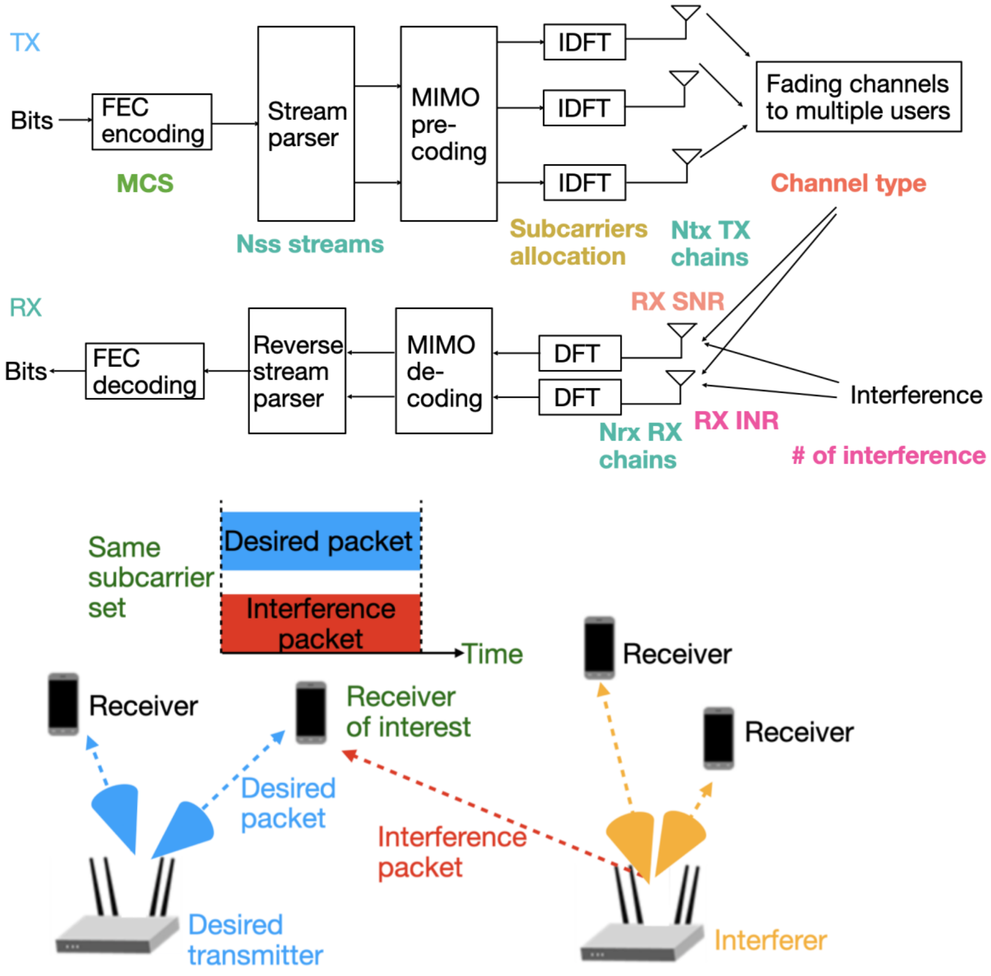
Error model

ns-3 WifiNetDevice example

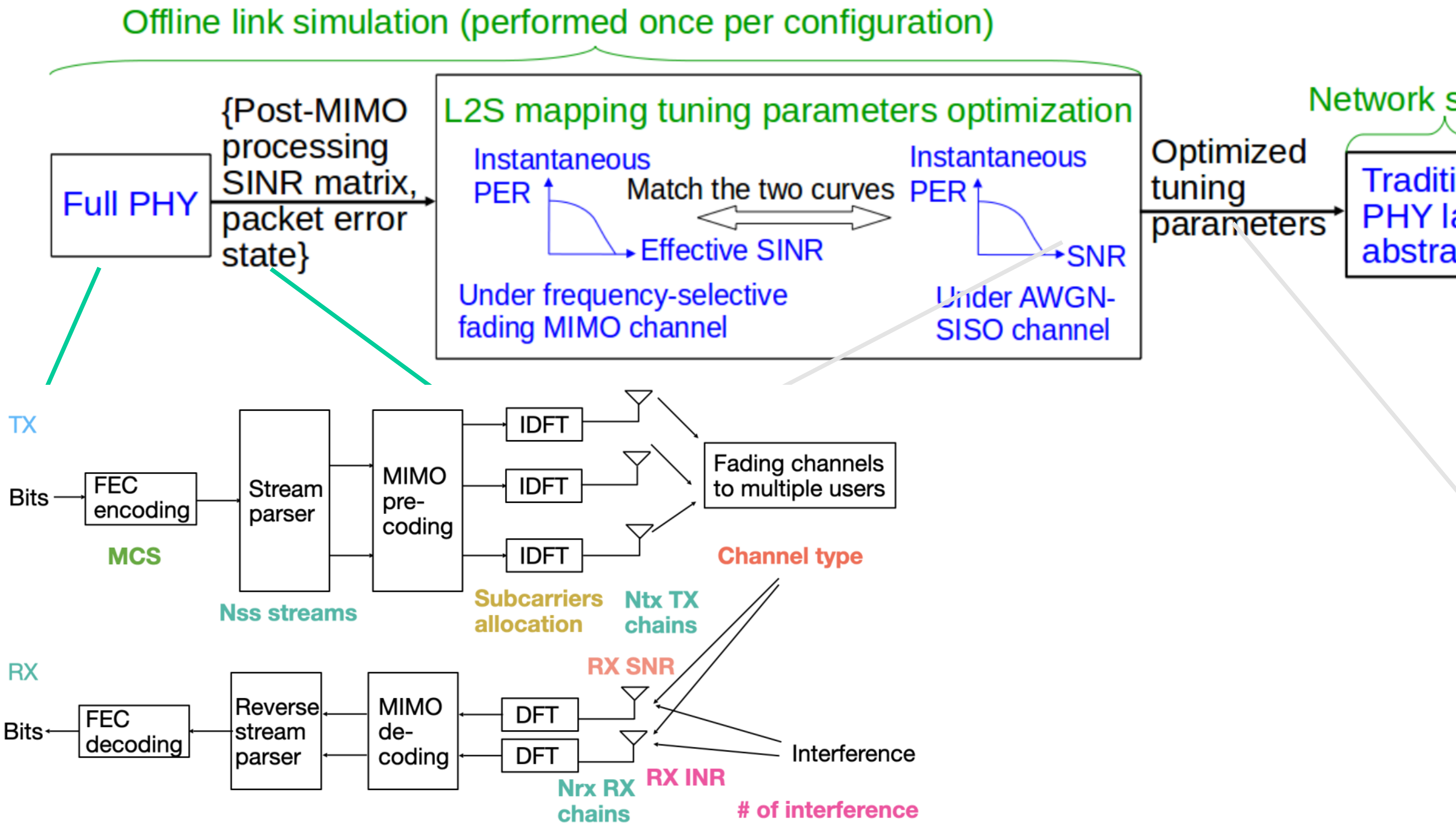
Issues with PHY layer abstractions

Exploding Complexity

- Increasing MIMO dimensions
- MU configurations (# streams per user profile)
- Higher Order Modulations
- Complex channels
- Greater co-channel interference (denser networks)
- Emphasis on *Network Efficiency*



L2S Implementation: IEEE TGax



Offline link simulation (performed once per configuration)

Full PHY

{Post-MIMO processing SINR matrix, packet error state}

L2S mapping tuning parameters optimization

Instantaneous PER

Effective SINR

Under frequency-selective fading MIMO channel

Match the two curves

Instantaneous PER

SNR

Under AWGN-SISO channel

Optimized tuning parameters

Network s

Traditi
PHY la
abstra

TX

Bits

FEC encoding

MCS

Stream parser

Nss streams

MIMO pre-coding

IDFT

IDFT

IDFT

Subcarriers allocation

Ntx TX chains

Fading channels to multiple users

Channel type

RX

Bits

FEC decoding

Reverse stream parser

MIMO de-coding

DFT

DFT

Nrx RX chains

RX SNR

RX INR

Interference

# of interference

[*] Appendix A of 11ax Evaluation Methodology (11-14-0571-12-00ax-evaluation-methodology.docx)

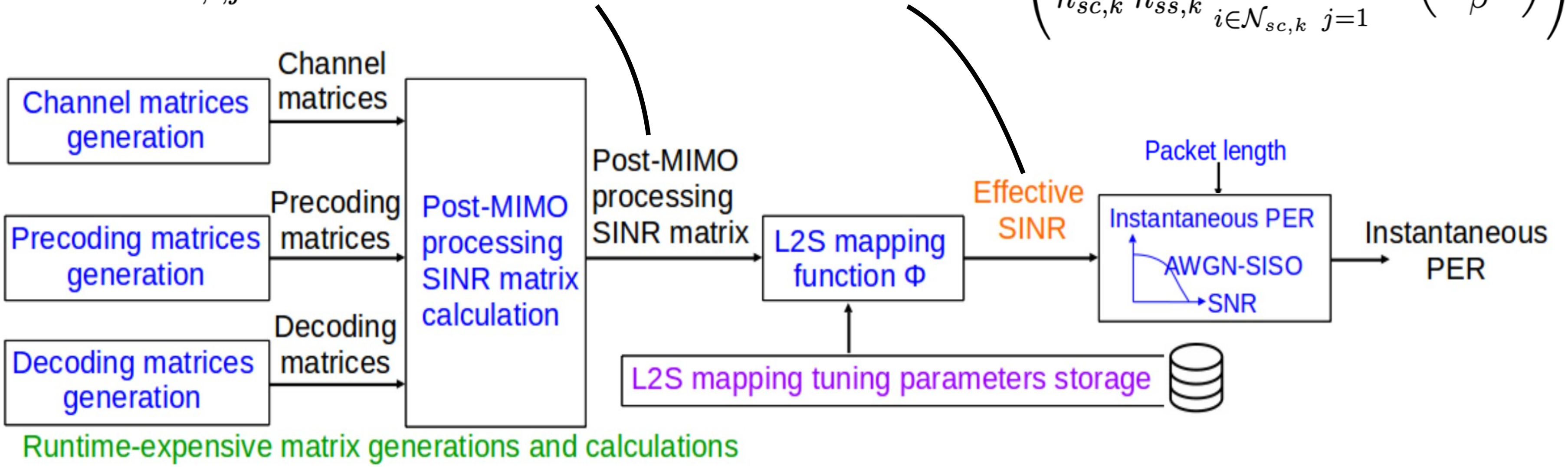
Traditional PHY layer abstraction [5]

L2S mapping suggested by IEEE TGax

L2S mapping functio

$$\Gamma^{sinr}_{eff,k} = \alpha\Phi^{-1}\left(\frac{1}{n_{sc,k}}\frac{1}{n_{ss,k}}\sum_{i\in\mathcal{N}_{sc,k}}\sum_{j=1}^{n_{ss,k}}\Phi\left(\frac{\Gamma_{k,i,j}}{\beta}\right)\right)$$

$\Gamma_{k,i,j}$ for i-th subcarrier and j-th stream



- L2S mapping function: EESM $\Gamma^{sinr}_{eff,k} = -\beta\ln\left(\frac{1}{n_{sc,k}}\frac{1}{n_{ss,k}}\sum_{i\in\mathcal{N}_{sc,k}}\sum_{j=1}^{n_{ss,k}}\exp\left(-\frac{\Gamma_{k,i,j}}{\beta}\right)\right)$

[5] IEEE TGax Group, “IEEE p802.11 Wireless Lans: 11ax Evaluation Methodology,” 2016.

Towards Fast Link-to-system (L2S) Mapping

Traditional link-to-system mapping approaches [*] (e.g. EESM) require generation of channel, pre-coding, decoding matrix instances to map to SINR per subcarrier, which are then compressed to a scalar *effective SINR*

- MIMO channel generation, MU operation, and matrix inversion pose limits: simulation run-time scales with the above !

Key Question/Insight: **Can effective SINR can be *directly* characterized from a link simulation campaign (i.e. bypassing channel generation etc. @ simulation run-time)?**

[*] Appendix A of 11ax Evaluation Methodology (11-14-0571-12-00ax-evaluation-methodology.docx)

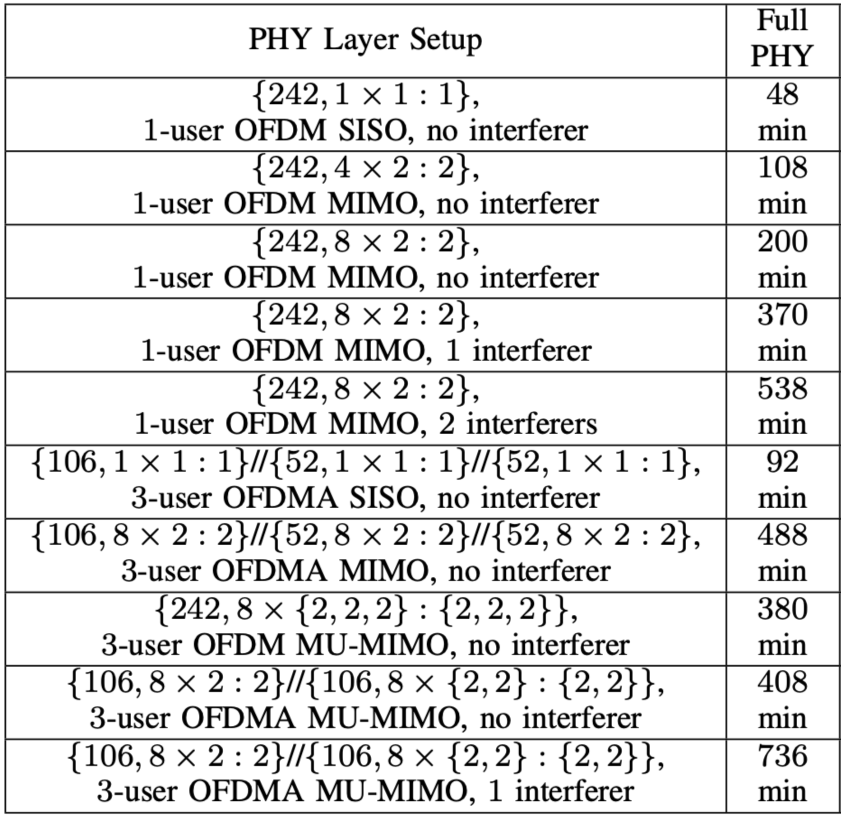
PHY layer complexity: runtimes

- Increasing MIMO dimensions
- Complex channels
- Greater interference (denser network)
- Higher order of MU transmissions

Very large runtime for running full PHY simulation (end-to-end encoding/decoding modulation/demodulating steps)

Need improved PHY layer abstractions: preserve simulation accuracy while reducing run-times

Single link, 40,000 packets, targeting [10^{-2}, 1] avg PER



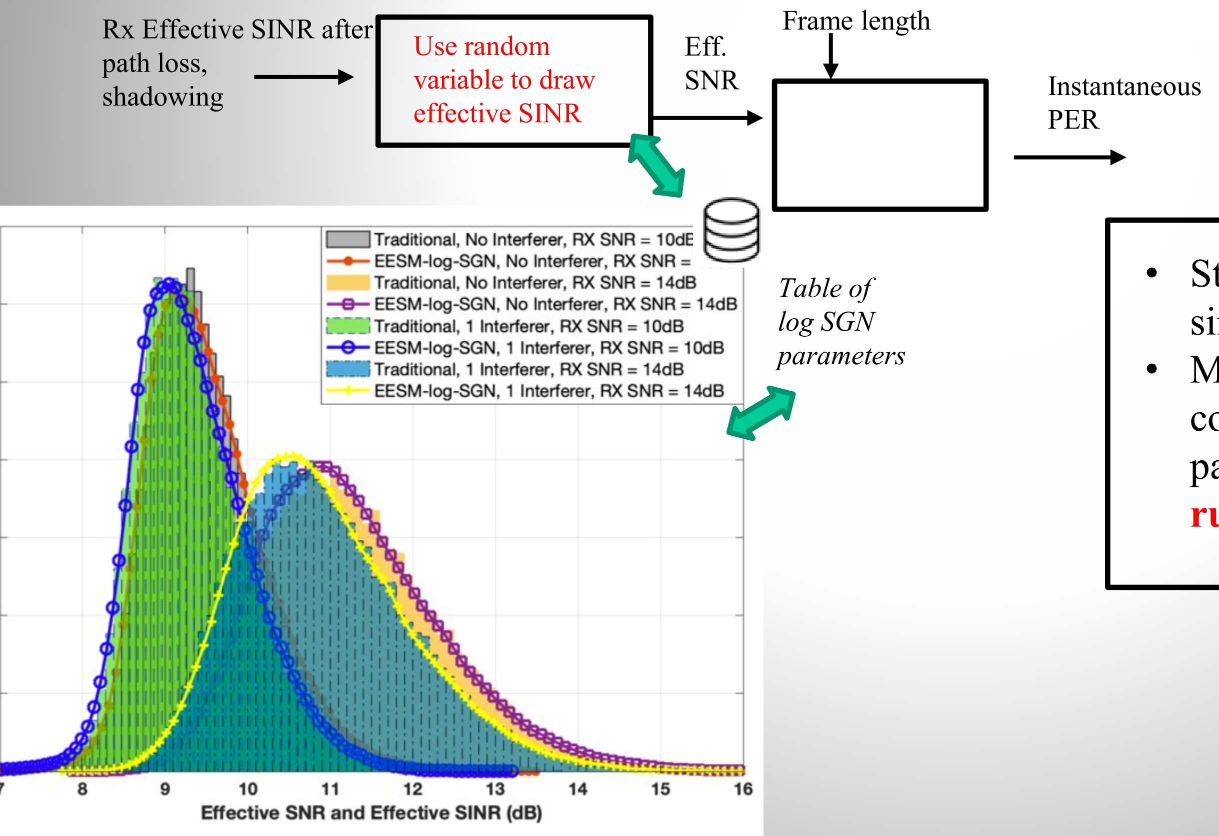
PHY Layer Setup	Full PHY
$\{242, 1 \times 1 : 1\}$, 1-user OFDM SISO, no interferer	48 min
$\{242, 4 \times 2 : 2\}$, 1-user OFDM MIMO, no interferer	108 min
$\{242, 8 \times 2 : 2\}$, 1-user OFDM MIMO, no interferer	200 min
$\{242, 8 \times 2 : 2\}$, 1-user OFDM MIMO, 1 interferer	370 min
$\{242, 8 \times 2 : 2\}$, 1-user OFDM MIMO, 2 interferers	538 min
$\{106, 1 \times 1 : 1\}//\{52, 1 \times 1 : 1\}//\{52, 1 \times 1 : 1\}$, 3-user OFDMA SISO, no interferer	92 min
$\{106, 8 \times 2 : 2\}//\{52, 8 \times 2 : 2\}//\{52, 8 \times 2 : 2\}$, 3-user OFDMA MIMO, no interferer	488 min
$\{242, 8 \times \{2, 2, 2\} : \{2, 2, 2\}\}$, 3-user OFDM MU-MIMO, no interferer	380 min
$\{106, 8 \times 2 : 2\}//\{106, 8 \times \{2, 2\} : \{2, 2\}\}$, 3-user OFDMA MU-MIMO, no interferer	408 min
$\{106, 8 \times 2 : 2\}//\{106, 8 \times \{2, 2\} : \{2, 2\}\}$, 3-user OFDMA MU-MIMO, 1 interferer	736 min

New PHY Link-to-System abstraction (log-SGN)

log-skew generalized normal (log-SGN) distribution can accurately characterize effective SINR with only a few parameters

$$X \triangleq \ln(\Gamma^{sinr}_{eff,k}) \sim \mathrm{SGN}(\hat{\mu}, \hat{\sigma}, \hat{\lambda}_1, \hat{\lambda}_2)$$

$$f_X(x; \hat{\mu}, \hat{\sigma}, \hat{\lambda}_1, \hat{\lambda}_2) = \frac{2}{\hat{\sigma}} \psi\left(\frac{x-\hat{\mu}}{\hat{\sigma}}\right) \Psi\left(\frac{\hat{\lambda}_1(x-\hat{\mu})}{\sqrt{\hat{\sigma}^2 + \hat{\lambda}_2(x-\hat{\mu})^2}}\right), \; x \in$$



Rx Effective SINR after path loss, shadowing

Use random variable to draw effective SINR

Eff. SNR

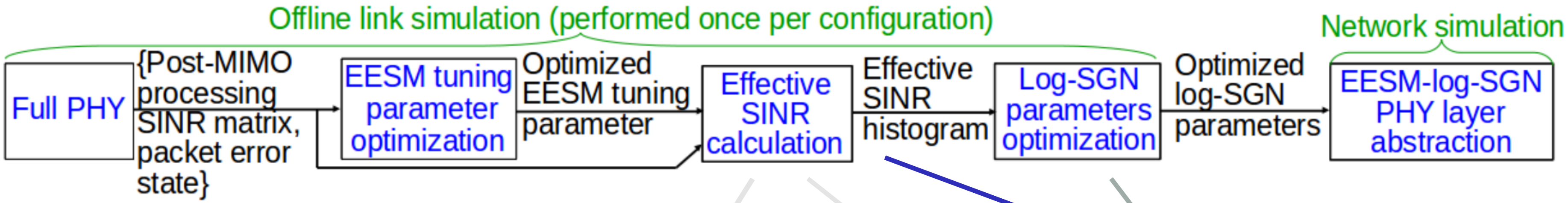
Frame length

Instantaneous PER

Table of log SGN parameters

- Still need to conduct full link simulation campaign
- Modest increase in storage complexity (vs. EESM or RBIR parameters), yields **dramatic runtime improvement**

Implementation Flow: Log-SGN L2S Method



Offline link simulation (performed once per configuration)

Network simulation

Full PHY

{Post-MIMO processing SINR matrix, packet error state}

EESM tuning parameter optimization

Optimized EESM tuning parameter

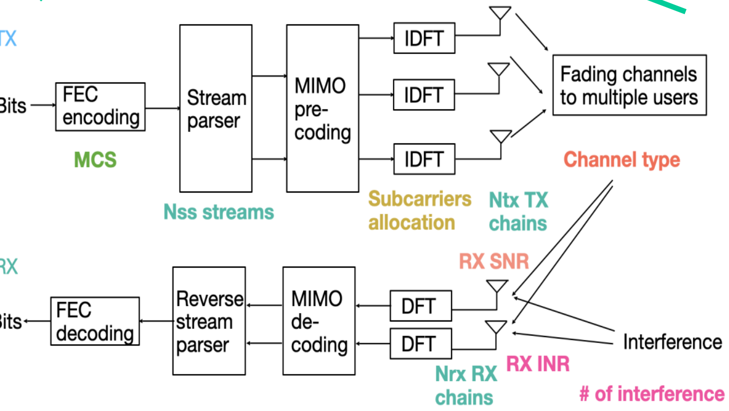
Effective SINR calculation

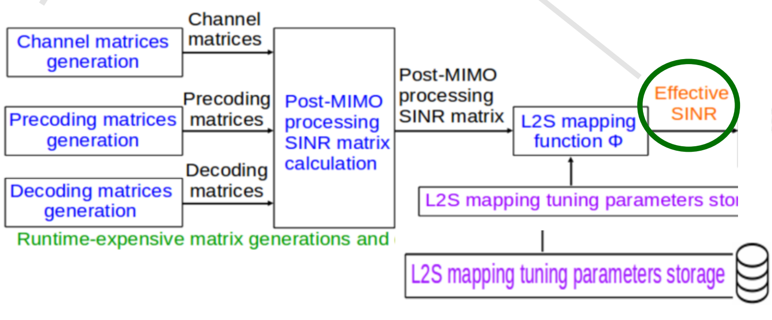
Effective SINR histogram

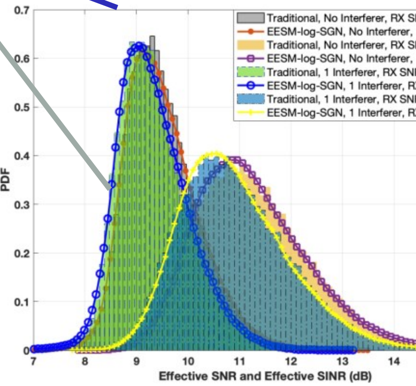
Log-SGN parameters optimization

Optimized log-SGN parameters

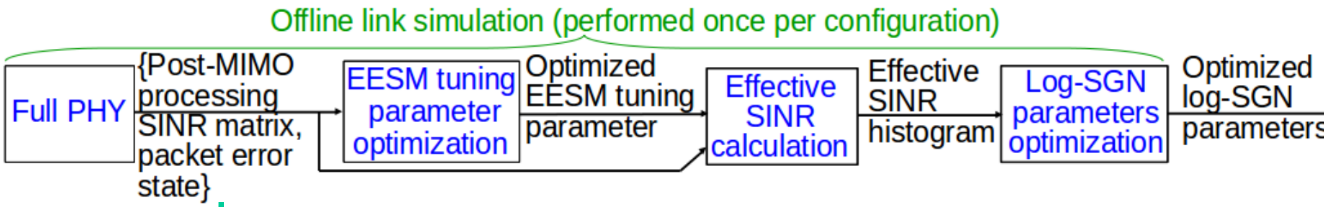
EESM-log-SGN PHY layer abstraction







PHY Configuration



Offline link simulation (performed once per configuration)

Full PHY

{Post-MIMO processing SINR matrix, packet error state}

EESM tuning parameter optimization

Optimized EESM tuning parameter

Effective SINR calculation

Effective SINR histogram

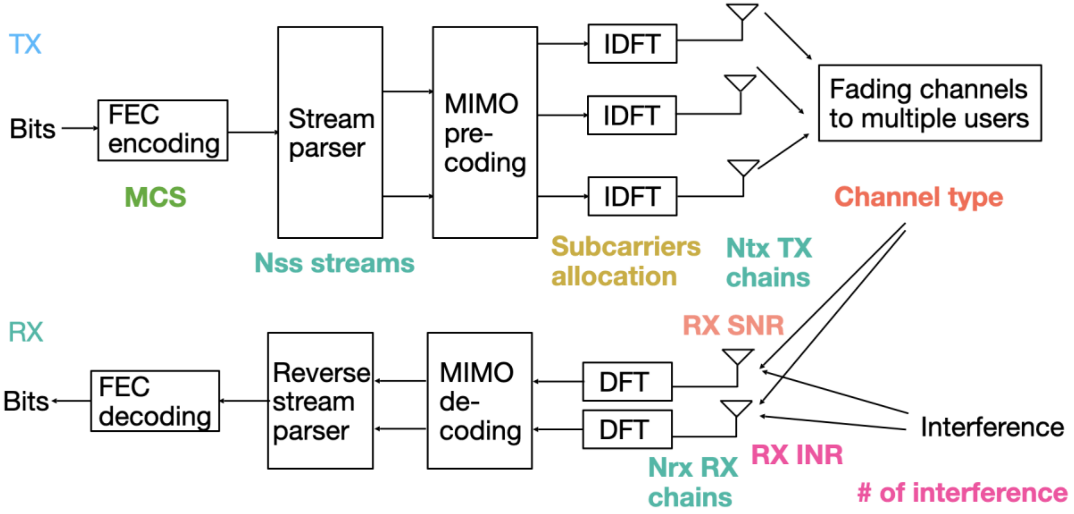
Log-SGN parameters optimization

Optimized log-SGN parameters

- Communication system: IEEE 802.11ax

Coding and modulation: LDPC at MCS 4

- OFDM with 242 subcarriers
- 1 × 1 SISO with 1 stream
- Channel type: TGax channel model-D
- RX SNR = TX SNR - path loss (dB)
- Interference-free case
- Simulate 4000 packets



TX

Bits

FEC encoding

MCS

Stream parser

Nss streams

MIMO pre-coding

IDFT

IDFT

IDFT

Subcarriers allocation

Ntx TX chains

Fading channels to multiple users

Channel type

RX

Bits

FEC decoding

Reverse stream parser

MIMO de-coding

DFT

DFT

Nrx RX chains

RX SNR

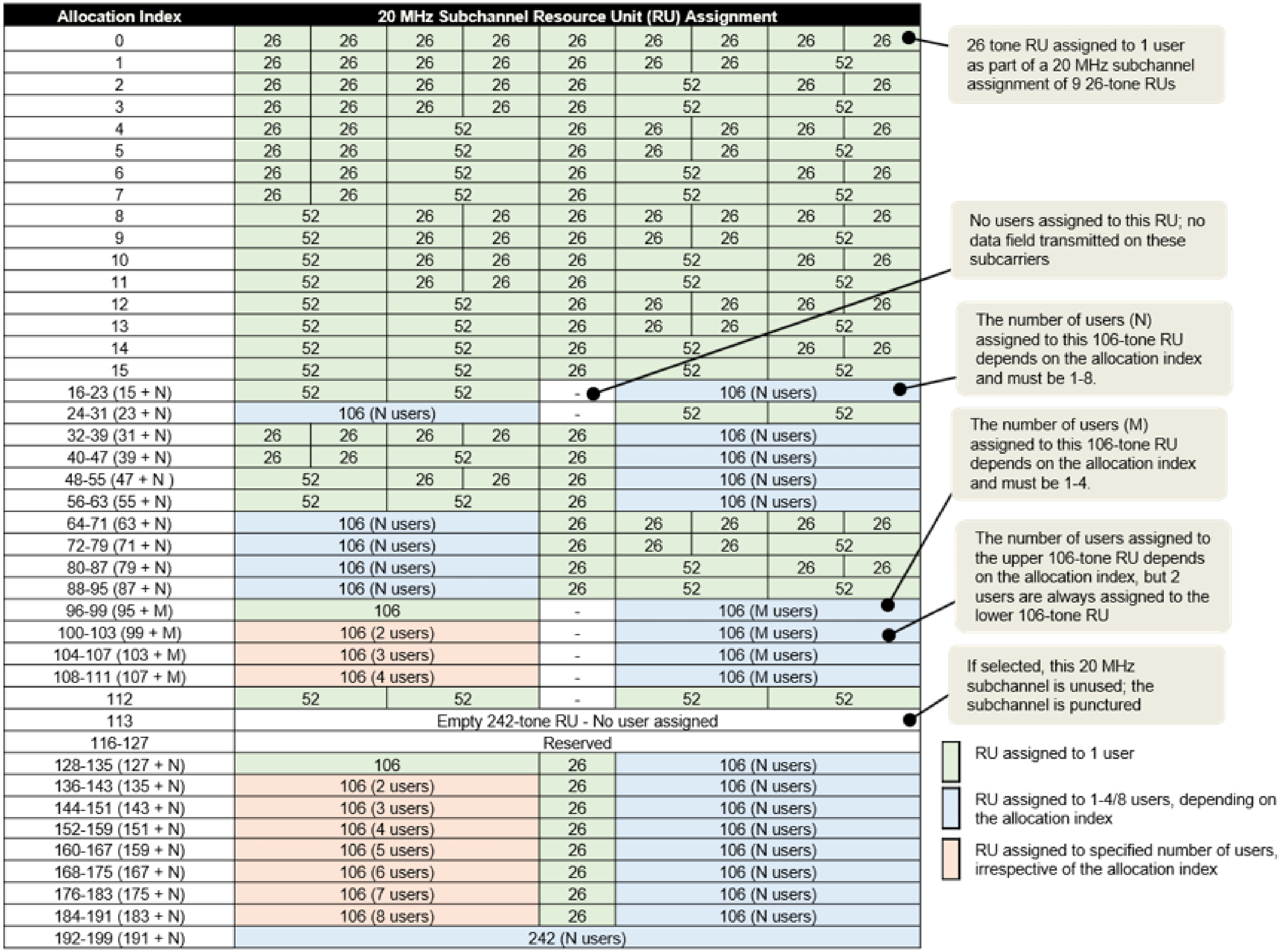
RX INR

Interference

# of interference

11ax subcarrier allocation

Full PHY simulation



Allocation Index	20 MHz Subchannel Resource Unit (RU) Assignment								
0	26	26	26	26	26	26	26	26	26
1	26	26	26	26	26	26	26	52	
2	26	26	26	26	26	52		26	26
3	26	26	26	26	26	52		52	
4	26	26	52		26	26	26	26	26
5	26	26	52		26	26	26	52	
6	26	26	52		26	52		26	26
7	26	26	52		26	52		52	
8	52		26	26	26	26	26	26	26
9	52		26	26	26	26	26	52	
10	52		26	26	26	52		26	26
11	52		26	26	26	52		52	
12	52		52		26	26	26	26	26
13	52		52		26	26	26	52	
14	52		52		26	52		26	26
15	52		52		26	52		52	
16-23 (15 + N)	52		52		-	106 (N users)			
24-31 (23 + N)	106 (N users)				-	52		52	
32-39 (31 + N)	26	26	26	26	26	106 (N users)			
40-47 (39 + N)	26	26	52		26	106 (N users)			
48-55 (47 + N)	52		26	26	26	106 (N users)			
56-63 (55 + N)	52		52		26	106 (N users)			
64-71 (63 + N)	106 (N users)				26	26	26	26	26
72-79 (71 + N)	106 (N users)				26	26	26	52	
80-87 (79 + N)	106 (N users)				26	52		26	26
88-95 (87 + N)	106 (N users)				26	52		52	
96-99 (95 + M)	106				-	106 (M users)			
100-103 (99 + M)	106 (2 users)				-	106 (M users)			
104-107 (103 + M)	106 (3 users)				-	106 (M users)			
108-111 (107 + M)	106 (4 users)				-	106 (M users)			
112	52		52		-	52		52	
113	Empty 242-tone RU - No user assigned								
116-127	Reserved								
128-135 (127 + N)	106				26	106 (N users)			
136-143 (135 + N)	106 (2 users)				26	106 (N users)			
144-151 (143 + N)	106 (3 users)				26	106 (N users)			
152-159 (151 + N)	106 (4 users)				26	106 (N users)			
160-167 (159 + N)	106 (5 users)				26	106 (N users)			
168-175 (167 + N)	106 (6 users)				26	106 (N users)			
176-183 (175 + N)	106 (7 users)				26	106 (N users)			
184-191 (183 + N)	106 (8 users)				26	106 (N users)			
192-199 (191 + N)	242 (N users)								

26 tone RU assigned to 1 user as part of a 20 MHz subchannel assignment of 9 26-tone RUs

No users assigned to this RU; no data field transmitted on these subcarriers

The number of users (N) assigned to this 106-tone RU depends on the allocation index and must be 1-8.

The number of users (M) assigned to this 106-tone RU depends on the allocation index and must be 1-4.

The number of users assigned to the upper 106-tone RU depends on the allocation index, but 2 users are always assigned to the lower 106-tone RU

If selected, this 20 MHz subchannel is unused; the subchannel is punctured

- 🟩 RU assigned to 1 user
- 🟦 RU assigned to 1-4/8 users, depending on the allocation index
- 🟧 RU assigned to specified number of users, irrespective of the allocation index

MathWorks, “802.11ax Parameterization for Waveform Generation and Simulation,” https://www.mathworks.com/help//wlan/ug/802-11ax-parameterization-for-waveform-generation-and-simulation.html.

Storage-complexity aspects

Handling wide range of RX SNRs and INRs

Fact: effective SNR/INR depends on RX SNR/INR

Challenge: can only store effective SNR/INR distribution for limited RX SNR/INR

Solution: interpolate effective SNR/INR for any RX SNR/INR using a small # of stored effective SNR distributions - mixture model

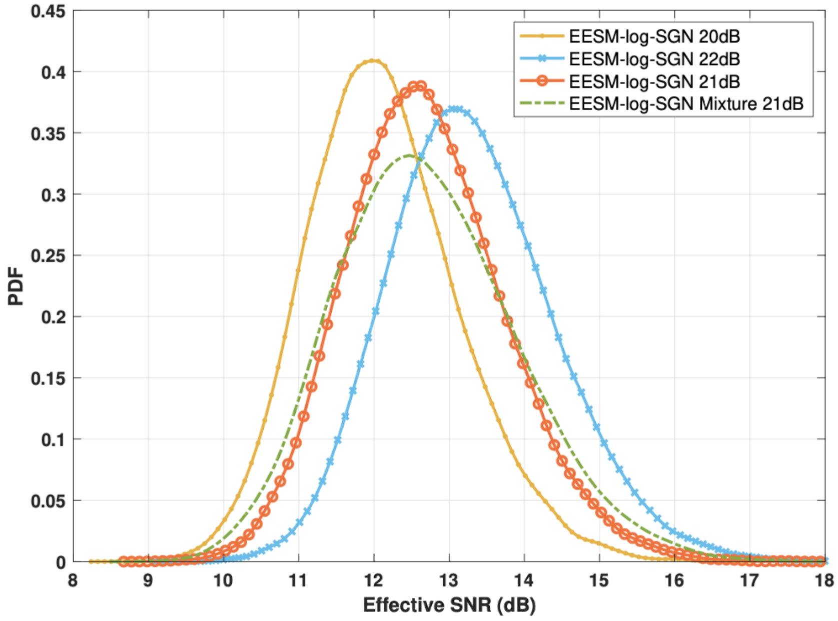
$$\hat{f}(\Gamma^{snr}_{eff,k};\gamma) = (1-\epsilon)f(\Gamma^{snr}_{eff,k};\gamma_1) + \epsilon f(\Gamma^{snr}_{eff,k};\gamma_2)$$

Estimated distribution

Stored distributions

Stored distributions

$$\epsilon = \frac{\gamma - \gamma_1}{\gamma_2 - \gamma_1}$$



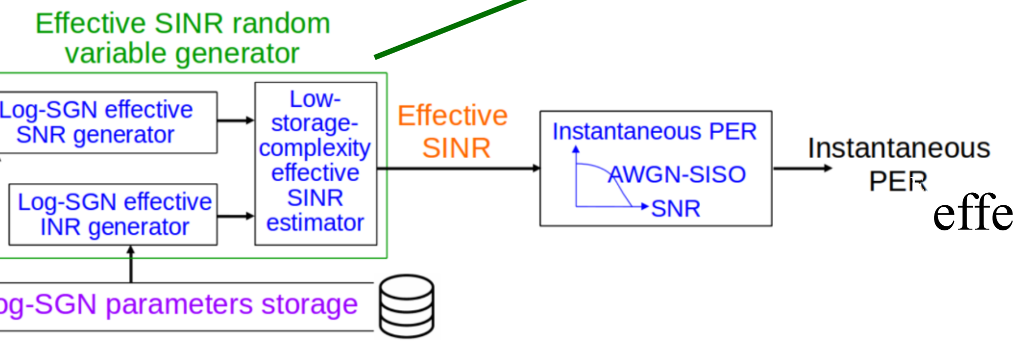
Storage-complexity aspects

Handling interference setups

Effective SNR $\Gamma^{snr}_{eff,k}$: effective SINR under the interference-free scenario with a certain RX SNR

Effective INR $\Gamma^{inr,v}_{eff,k}$: effective SINR with signal from an interferer v only and with a certain RX INR

Solution: estimate effective SINR from effective SNR & effective INR - low storage complexity (LSC) solution



Effective SNR

|V|: # of interferers

$$\hat{\Gamma}^{sinr}_{eff,k} = \frac{\Gamma^{snr}_{eff,k}}{1+\theta\sum_{v\in\mathcal{V}}\Gamma^{inr,v}_{eff,k}}$$

effective SINR

Effective INR

References, Code

- Matlab 2020b and WLAN Toolbox or later version
- Matlab Code for 11ax PHY Abstraction : https://github.com/sianjin/EESM-log-SGN
- ns-3 code: https://gitlab.com/sderonne/ns-3-11be/-/tree/log_sgn_ofdma_mu_mimo_phy_abstraction

- https://depts.washington.edu/funlab/projects/improvements-to-ns-3- simulator/ns-3-scaling-for-next-g-wireless-networks/
- S. Jin, S. Roy and T. R. Henderson, ``Efficient PHY Layer Abstraction for Fast Simulations in Complex System Environments," IEEE Trans. Comm., Aug.2021.
- w-ns3 2021 Tutorial https://www.nsnam.org/wp-content/uploads/2021/tutorials/EESM-log-SGN-tutorial.pptx

Status

- **PHY Abstraction → SU-MIMO complete**: with & without beamforming
- **PHY Abstraction → MU-MIMO**
  - Downlink complete: with beamforming under all DL MU-MIMO configurations
  - Uplink in-progress: with beamforming, support single-antenna UE (UL MU-SIMO)

❖ Beamforming feedback: no delay and noise in channel sounding presently; additive CSI error to model impact of channel sounding in progress

CCA

- Conditions for CCA BUSY on primary 20 MHz channel (11ax 27.3.20.6.3)
- CCA sensitivity for signals not on primary 20 MHz (11ax 27.3.20.6.4)
- Per 20 MHz CCA sensitivity (11ax 27.3.20.6.5)

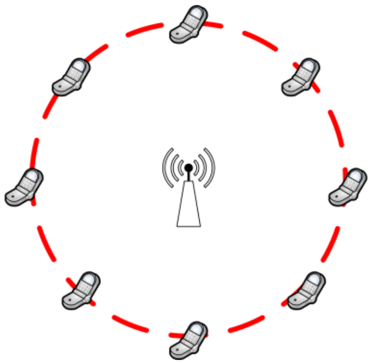
https://depts.washington.edu/funlab/projects/improvements-to-ns-3- simulator/ns-3-scaling-for-next-g-wireless-networks/

Performance Evaluation Case Studies

- **Single BSS DCF Validation** (saturated traffic)
  - known analytical results [Bianchi …]

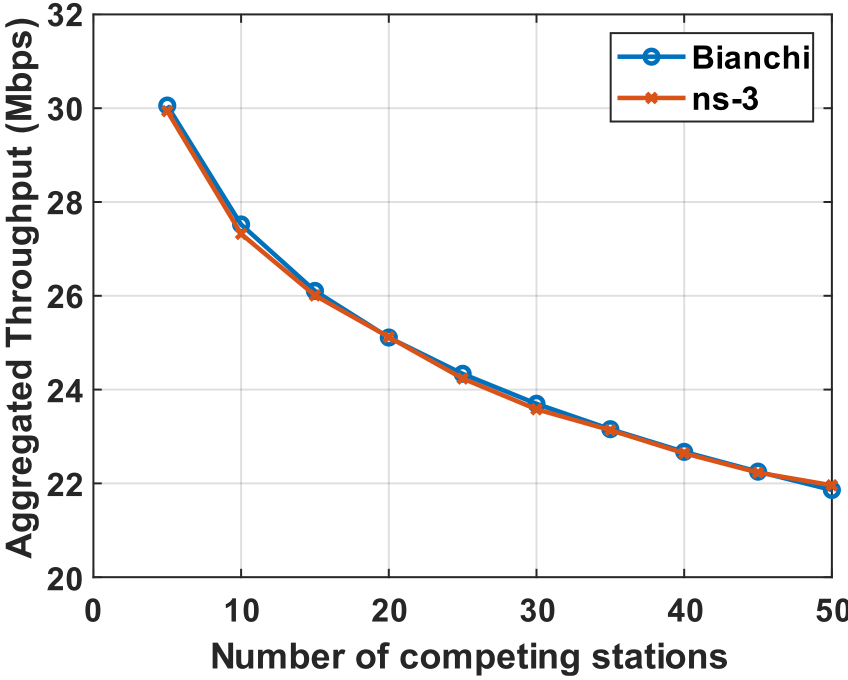
- **multi BSS DCF network performance**
  1. Throughput analysis and validation
  2. CCA Threshold Optimization
     - Analysis the impact of CCA
     - 802.11 TGax Simulations
     - CCA Optimization with ns3-ai

Validate WiFi module in ns-3: Single BSS T’put



- Simulation setup:
  - Infrastructure mode: One AP and multiple stations
  - Traffic: Uplink traffic only.
  - Stations located at the same distance (circle) from AP
  - Transmission: fixed identical power and MCS
  - Saturation mode

- Key assumptions for the analytical model:
  - No PHY errors → packet losses only caused by collision
  - STA all identical



[1] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," in *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535-547, March 2000

DCF validation

- https://gitlab.com/nsnam/ns-3-dev/-/blob/master/src/wifi/examples/wifi-bianchi.cc

Throughput – Multi-BSS analysis

Axis:

AP1 (0, 0) AP2 (d, 0)

STAs (0, r) STAs (d, r)

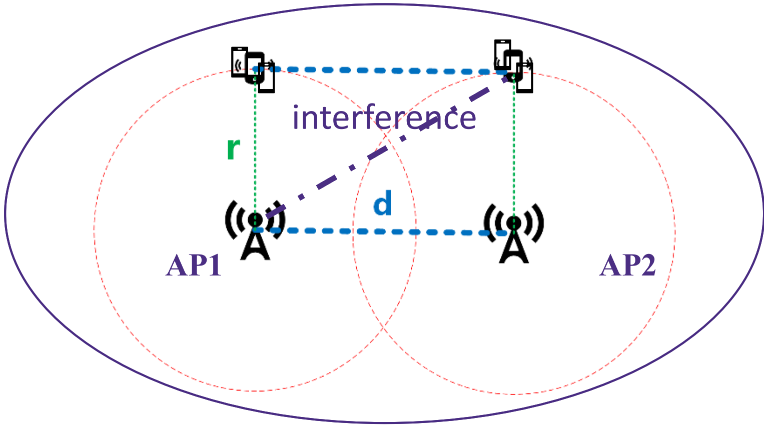
2 Overlapping BSS [2]:

- Parameters ***d*** (inter-BSS distance), ***r*** (BSS transmission range) → different SINR
- Variable # STA per BSS, ALL at same location
- CCA threshold: -82 dBm, TX power: 20 dBm
  - CCA Range: 30 meters
- Log distance path loss (PL) model
- Uplink traffic only

$$\text{SINR} = \frac{P_{rx}}{(P_{int}+Noise)}$$

$$P_{rx} = P_{tx} - PL(r)$$

$$P_{int} = P_{tx} - PL(\sqrt{r^2 + d^2})$$



CCA Range = 30 m

MCS	PER = 0.01
0	4.58 dB
2	10.53 dB
4	17.31 dB
6	23.35 dB
8	29.24 dB

SINR required for PER, packet size 1500 bytes

Conditions that 2 STAs can transmit ***successfully*** simult:

- 2 STAs are in different BSS
- SINR > *Threshold(MCS)*, for example, we need around 5 dB SNIR for MCS 0
- **Both** transmissions can succeed in this symmetric topology

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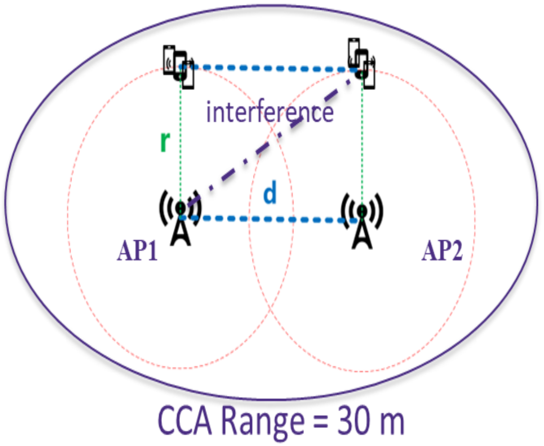
[2] R. Kajihara, H. Wenkai, L. Lanante, M. Kurosaki and H. Ochi, "Performance Analysis Model of IEEE 802.11 CSMA/CA for Multi-BSS Environment," 2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications, 2020, pp. 1-7, doi: 10.1109/PIMRC48278.2020.9217235.

Throughput – Multi-BSS analysis

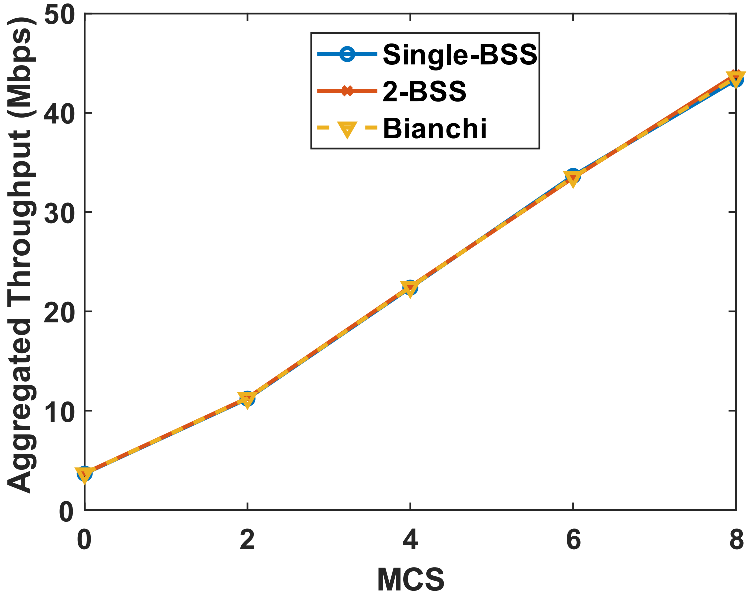


Case 1: Two BSS T'put equiv. One large BSS

- Setup: Total 50 STAs (25 STAs in each BSS)
  - r = 8m, d = 5m, $\sqrt{r^2 + d^2}$ = 9.5m, SINR = 2 dB
  - SINR = 2 dB → No successful simult. transmissions for ALL MCS
  - ALL nodes within a carrier sensing range of 30 m (i.e., can sense each other)
  - 2 BSS ~ One larger cell

❖ Results:

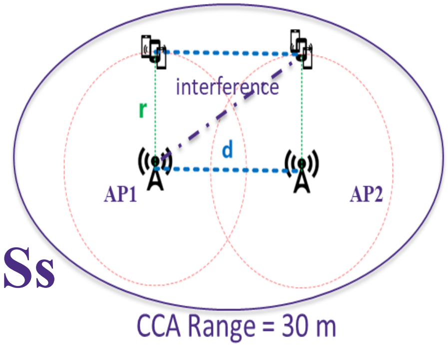
Parameters	Value
P_{rx}	-61.6 dBm
P_{in}	-64.6 dBm
Noise	-128 dBm
SINR	2 dB



- Results validated against Bianchi model predictions

Example Codes: https://gitlab.com/haoyinyh/ns-3-dev/-/tree/multibss

Throughput – Multi-BSS analysis

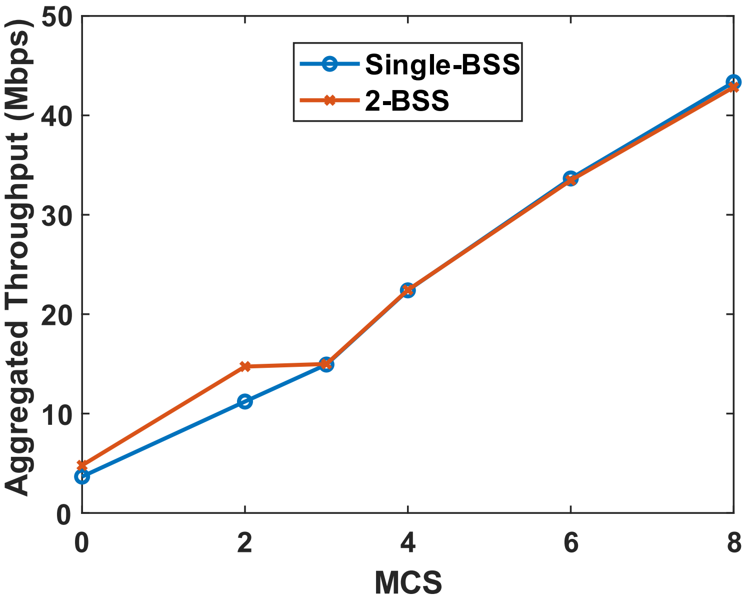


Case 2: Successful Simultaneous transmission @ low MCSs

- Setup: Total 50 STAs (25 STAs in each BSS)
  - $r = 10\text{m}, d = 20\text{m}, \sqrt{r^2 + d^2} = 22.3\text{m}$, SINR = 12 dB
  - SINR = 12 dB → Can support successful simult. transmission at MCS 0/1/2
  - ALL nodes within a carrier sensing range of 30 m (i.e., can sense each other)
  - Expectation: 2 BSS has larger throughput in MCS 0/1/2 than one large cell

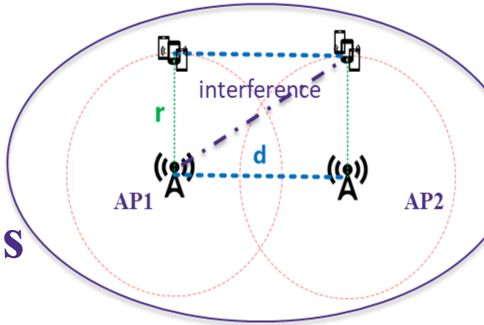
❖ Results:

Parameters	Value
P_{rx}	-65 dBm
P_{in}	-77.2 dBm
Noise	-128 dBm
SINR	12 dB



- Simultaneous transmission happens when MCS < 3
  → multi-BSS throughput is larger when MCS < 3
- Large single BSS throughput validated against the Bianchi model (similar to Case 1)

Throughput – Multi-BSS analysis



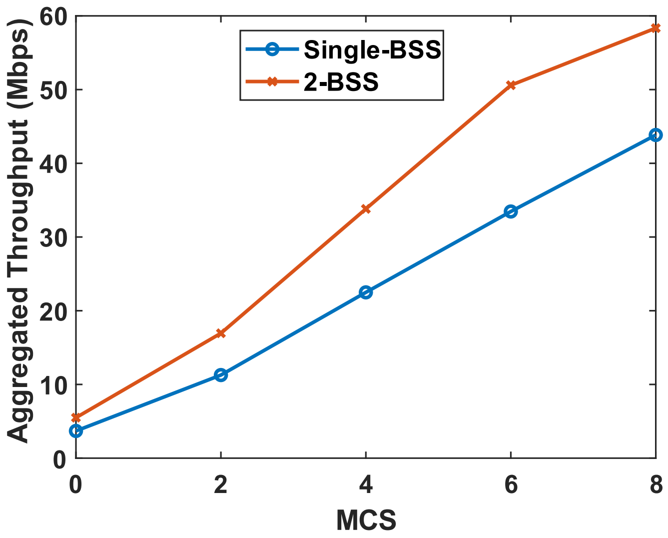
CCA Range = 30 m

Case 3: Successful Simultaneous transmission @ all MCSs

- Setup: Total 50 STAs (25 STAs in each BSS)
  - r = 3m, d = 20m, $\sqrt{r^2 + d^2}$ = 20.3m, SINR = 28.9 dB
  - SINR = 28.9 dB → Can support successful simult. transmission at all MCSs
  - ALL nodes within a carrier sensing range of 30 m (i.e., can sense each other)
  - Expectation: 2 BSS has larger throughput for all MCSs than one large cell

❖ Results:

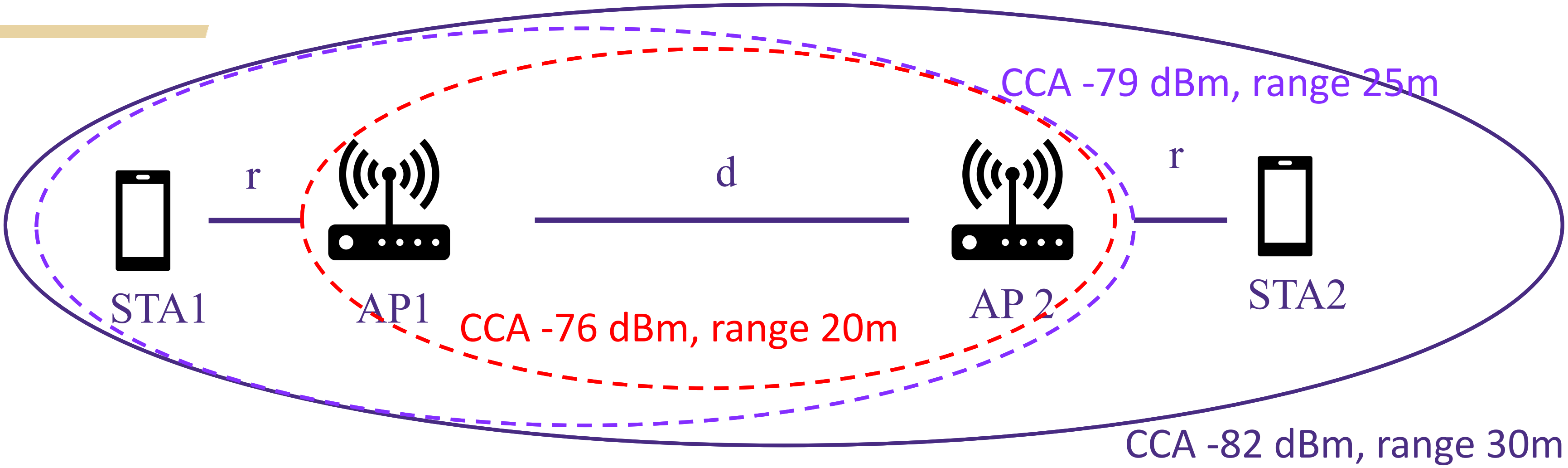
Parameters	Value
P_{rx}	-46.7 dBm
P_{in}	-75 dBm
Noise	-128 dBm
SINR	28.9 dB



- Simultaneous transmission happens for all MCSs → multi-BSS throughput is UNIFORMLY larger
- Large single BSS throughput validated against the Bianchi model (similar to Case 1)

Can we adjust universal CCA threshold over all BSSs to gain FURTHER from successful simultaneous transmission? (Future: **New feature in 802.11ax: BSS coloring: Backup Slide**)

Changing CCA: Simple 2-BSS case



r = 5 m, d=20 m, P_{tx} = 20 dBm

At STA1

$P_{rx1}(STA2) = P_{tx}(STA2) - PL(r+d+r) = -82$ dBm

$P_{rx1}(AP2) = P_{tx}(AP2) - PL(r+d) = -79$ dBm

At AP1

$P_{rx1}(STA2) = P_{tx}(STA2) - PL(r+d) = -79$ dBm

$P_{rx1}(AP2) = P_{tx}(AP2) - PL(d) = -76$ dBm

Interference from STA2 at AP1: $\text{SINR(AP1)} = \frac{P_{rx}(STA1)}{(P_{rx}(STA2)+Noise)} = 24$ dB

Interference from AP2 at AP1: $\text{SINR(AP1)} = \frac{P_{rx}(STA1)}{(P_{rx}(AP2)+Noise)} = 21$ dB

Log distance propagation model

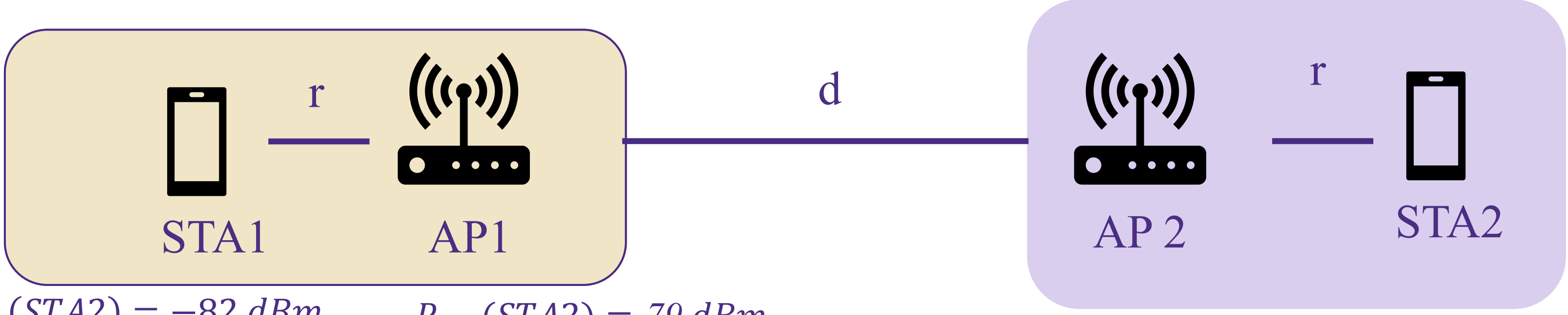
$$PL(dis) = L_0 + 10 * n * \log_{10}\left(\frac{dis}{d_0}\right)$$

n: the path loss distance exponent, n=3.5

d_0: reference distance, $d_0 = 1\,m$

L_0 : path loss at reference distance (dB), $L_0 = 50$

Changing CCA: Simple 2- BSS case



$P_{rx1}(STA2) = -82\ dBm$
$P_{rx1}(AP2) = -79 dBm$

$P_{rx1}(STA2)$ =-79 dBm
$P_{rx1}(AP2)$ =-76 dBm

Change CCA thresholds:

- Case1: 2-BSS all within the CCA range (CCA <= -82 dBm)
- Case2: 2-BSS, STA1 can't hear STA2 (-82<CCA<= -79 dBm)
- Case3: 2-BSS, STA1 can't hear Network2 (-79<CCA<= -76 dBm)
- Case4: 2-BSS, Network 1 and 2 can't hear each other (CCA > -76 dBm)

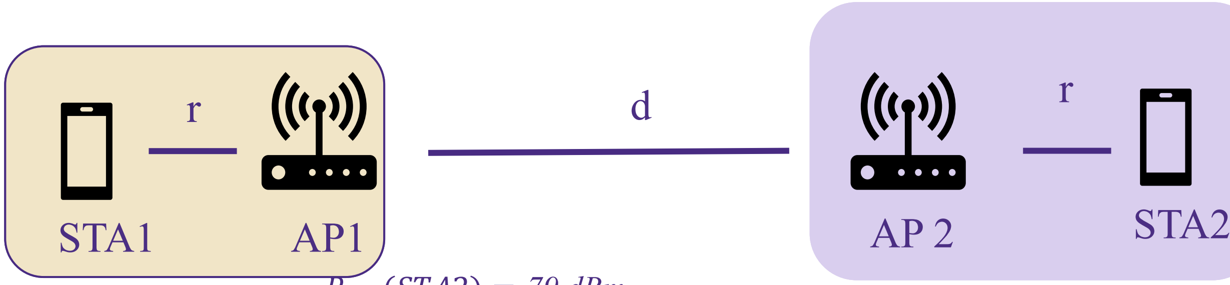
Packet error rate for different MCSs and SINR

MCS	$P_e(24\ dB)$	$P_e(21\ dB)$
0-4	0	0
5	0	0.27
6	0.001	0.99
7	0.05	1
8	1	1

$$\text{SINR(AP1)} = \frac{P_{rx}(STA1)}{(P_{rx}\ (STA2)+Noise)} = 24 \text{ dB: STA1 collides with STA2 at AP1}$$

$$\text{SINR(AP1)} = \frac{P_{rx}(STA1)}{(P_{rx}\ (AP2)+Noise)} = 21 \text{ dB: STA1 collides with AP2 (ACK) at AP1}$$

Simulation Results



$P_{rx1}(STA2) = -82\ dBm$

$P_{rx1}(AP2) = -79\ dBm$

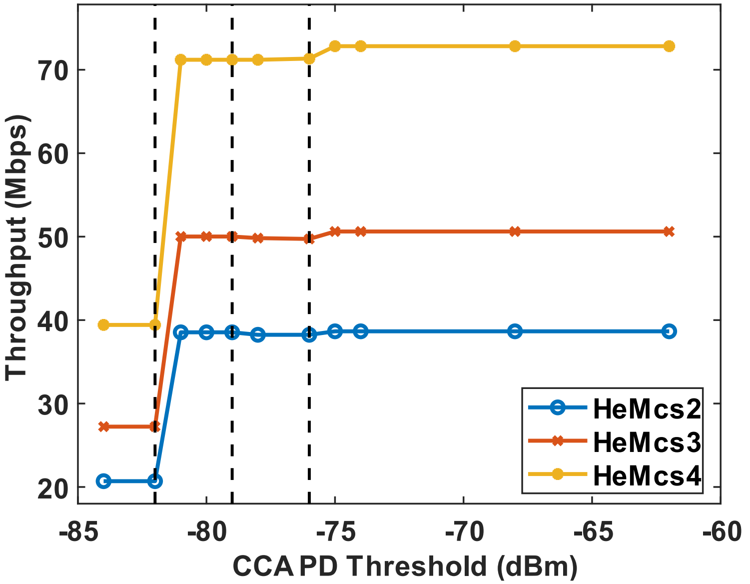
$P_{rx1}(STA2) = -79\ dBm$

$P_{rx1}(AP2) = -76\ dBm$

Traffic:
UL Only, 2 Nodes (one AP ,one STA) in each network

MCS	$P_e(24\ dB)$	$P_e(21\ dB)$
0-4	0	0
5	0	0.27
6	0.001	0.99
7	0.05	1
8	1	1

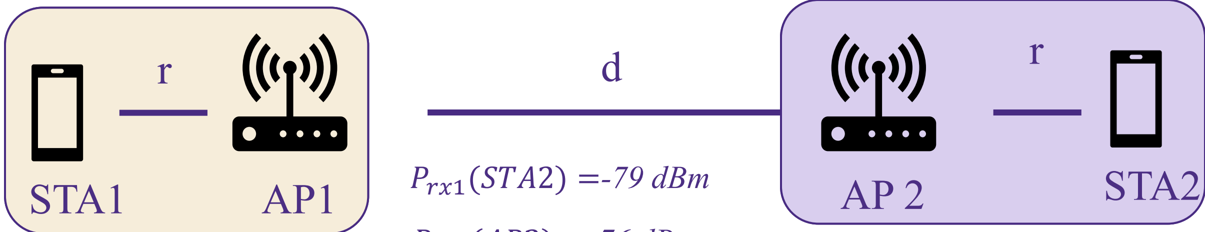
Packet error rate for different MCSs and SINR



MCS	Single BSS	CCA <= -82	CCA > -76	2*Single BSS
2	19.3	20.7	38.7	38.6
3	25.3	27.2	50.6	50.6
4	36.4	39.4	72.8	72.8

- STA1 and STA2 can have two successful simultaneous transmission at MCS 0-4
- As CCA threshold increases → throughput increases
- After the CCA > -76 dBm: two networks can't hear each other, and aggregate throughput is doubled compared with single BSS

Simulation Results



$P_{rx1}(STA2)$ =-79 dBm

$P_{rx1}(AP2)$ =-76 dBm

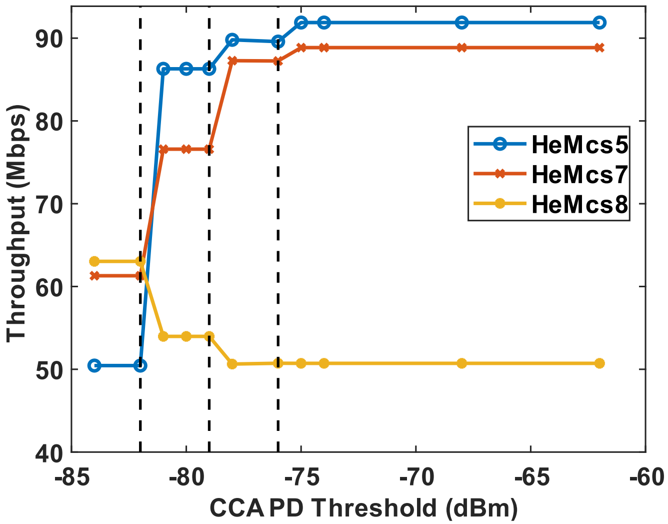
$P_{rx1}(STA2) = -82\ dbm$

$P_{rx1}(AP2) = -79\ dbm$

Traffic:
UL Only, 2 Nodes (one AP, one STA) in each network

Packet error rate for different MCSs and SINR

MCS	$P_e(24\ dB)$	$P_e(21\ dB)$
0-4	0	0
5	0	0.27
7	0.05	1
8	1	1



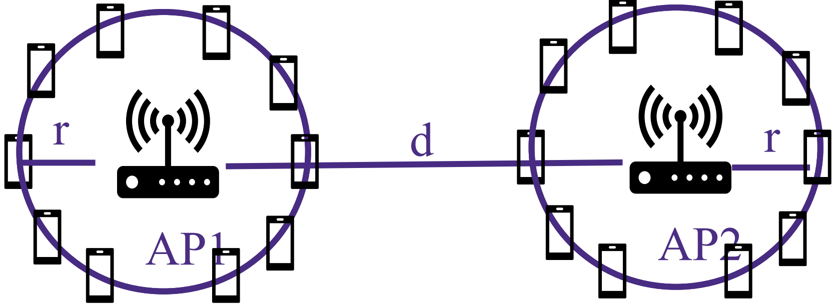
MCS	Single BSS	CCA <= -82	CCA > -76	2*Single BSS
5	46.3	50.4	91.9	92.6
7	51.4	61.2	88.9	102.8
8	56.1	63.0	50.7	112.2

- STA1 and STA2 will see errors when two network have simultaneous transmission

→ For MCS 5-7, error rate is low when two STAs transmit, throughput increases as CCA increases but < 2x single network t'put

→ For MCS8, two STAs can't have any simultaneous transmission. As CCA increases, hidden terminals occur and leads to large throughput drop !

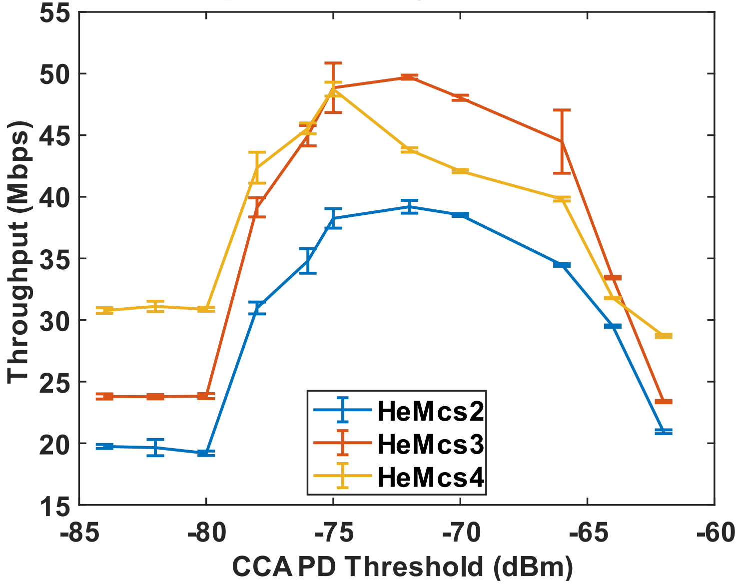
More complex cases: nSTA > 2

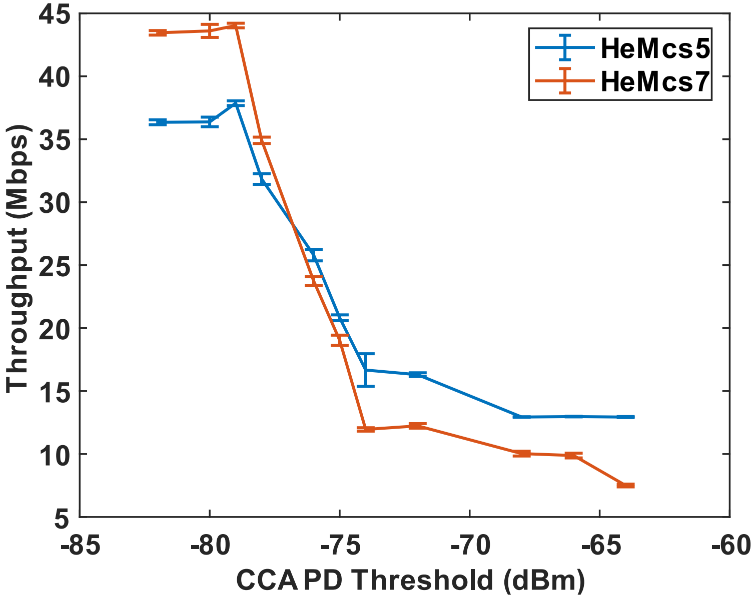


More stations (nSTA = 10), distributed on a circle, r = 5m, d = 20m, $P\_tx = 20$ dBm:

→ Different interference level: -82 dBm < P_{rx1} < -69 dBm

- Optimization of CCA: **trade-off between hidden and exposed terminals**
  - As MCS increases, optimal throughput achieved @ lower CCA threshold since it requires a higher SINR for success





Analysis in [4] to find the optimal CCA threshold for a homogeneous network with constant link distances.

[4] H. Ma, R. Vijayakumar, S. Roy and J. Zhu, "Optimizing 802.11 Wireless Mesh Networks Based on Physical Carrier Sensing," in IEEE/ACM Transactions on Networking, vol. 17, no. 5, pp. 1550-1563, Oct. 2009, doi: 10.1109/TNET.2008.2009443.

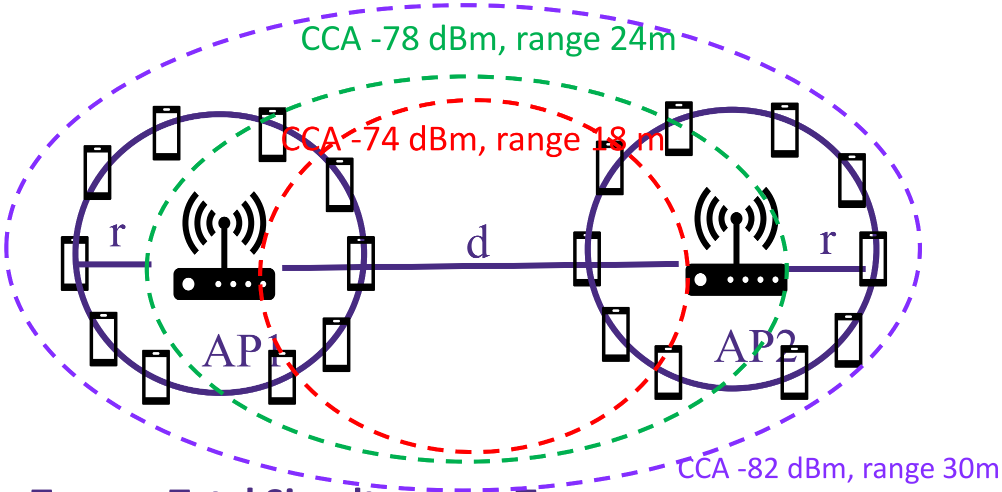
ns-3 Simulations: PHY Reception Failure Cases

Results: For 2 BSSs, the failure/success probability vs PD threshold

nSTA=10 Per BSS

r = 5 m, d=20 m, P_{tx} = 16 dBm, same log distance pathloss model

AMPDU disabled

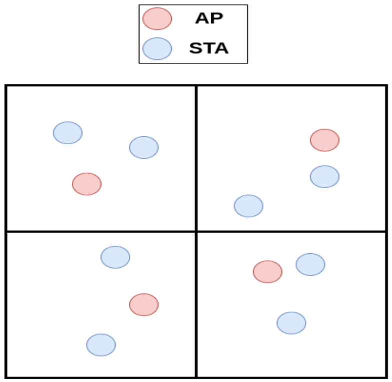


For MCS = 4 **Percentage of Failed Simultaneous Tx over Total Simultaneous Tx**

CCA (dBm)	CCA Range (m)	Total Tx	Total Simult Tx (% over Total Tx)	Failed Simult Tx (% over Total Simult Tx)	Intra-BSS Success (% over Total Simult Tx)	Inter-BSS Success (% over Total Simult Tx)	Data Collision During HE Preamble (% over Total Simult Tx)	Data Collision During Payload (% over Total Simult Tx)	Aggregated Throughput (Mbps)
-82	30	84529	24039 (28%)	16783 (69.81%)	0	7256 (30.18%)	16743 (69.65%)	0	28.11
-78	24	84775	24474 (28%)	16604 (67.84%)	0	7870 (32.15%)	16267 (66.46%)	307 (1.25%)	28.35
-74	18	119333	65261 (54%)	23224 (35.58%)	0	42035 (64.41%)	19095 (29.25%)	4100 (6.28%)	40.27
-70	14	91541	31943 (34%)	9609 (30.08%)	0	22334 (69.91%)	7876 (24.64%)	1707 (5.34%)	27.73
-66	11	90704	29019 (31%)	6514 (22.44%)	0	22505 (77.55%)	6049 (20.82%)	446 (1.53%)	26.06
-62	8	96185	41874 (43%)	19790 (47.26%)	31 (0.07%)	22053 (52.66%)	10244 (24.44%)	9231 (22.04%)	20.84

*in this table - small amount of PHY reception failure such as "TXING“ happen due to beacon + data collisions not accounted for

802.11ax TGax Residential Scenario



- Each apartment - square with dim. X m. by X m.
- All STAs associate with AP in its own apartment/cell
- AP and STAs are randomly distributed in the square
- TGax defined pathloss for this scenario:

$$PL(d) = 40.05 + 20 * \log_{10}\left(\frac{fc}{2.4}\right) + 20\log_{10}(min(d,5)) + 18.3 * (d)^{\left(\frac{((d)+2)}{(((d)+1)-0.46)}\right)} + 5(walls)$$

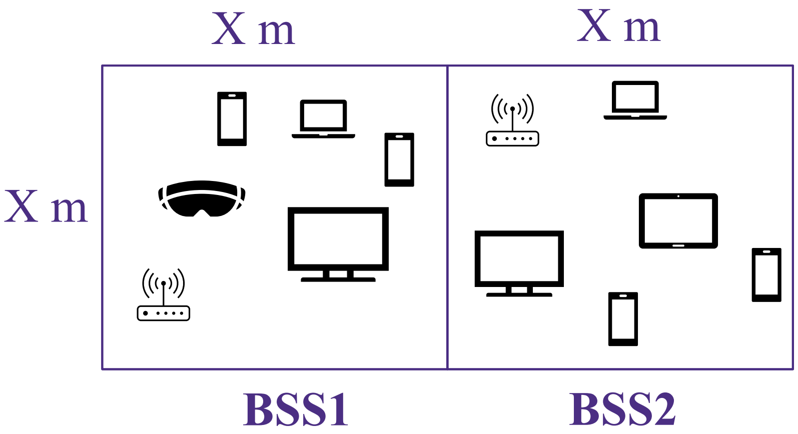
- Consider ***mixed traffic types***
  - VR/AR burst traffic: ns-3 VR traffic model [5]
  - CBR traffic as background

Distance to AP	MCS	Distance to AP	MCS
< 11 m	11	27 m	6
12 m	10	29 m	5
13 m	9	31 m	4
18 m	8	42 m	3
26 m	7	52 m	2

- **Auto MCS Allocation**:
  - For each STA, fix MCS based on the distance to the AP
  - Choose the MCS that achieves less than 1% PER

[5] M. Lecci, M. Drago, A. Zanella, M. Zorzi, "An Open Framework for Analyzing and Modeling XR Network Traffic," in IEEE Access, vol. 9, pp. 129782-129795, 2021. Open Access DOI: 10.1109/ACCESS.2021.3113162. Code: https://github.com/signetlabdei/ns-3-vr-app

VR/AR Gaming Scenario



Typical VR/AR Scenario Overview

- **Room 1**: One VR device, four other non-VR devices (Phone, TV, iPad, PC, etc.)
- **Room 2**: Five non-VR devices, classified as "Best Effort"
- VR Latency constraint: Mean HOL delay <= 5 ms

Can we adjust CCA PD in BSS1 to

- **Fulfill the latency constraint & data rate for VR**
- **Maximize aggregate throughput of network**

CCA-PD (dBm)	CCA-Range intra-BSS (m)	CCA-Range OBSS (m)
-82	45	32
-78	35	25
-74	23	19
-70	20	15
-66	16	11
-62	12	8

Example Setups (scenario complexity)

- AP and STA randomly distributed in 25m x 25m square
- AP & STA TX Power: 12 dBm
- TGax indoor pathloss model
- One VR Node in BSS-1:
  - VR Traffic Rate: 14.7Mbps, 30 Hz refresh rate: one 0.49 MB
- Other Nodes Traffic: Per-USER CBR 4 Mbps
- Total Number of STAs per BSS: 5, Auto MCS
- change CCA PD on BSS1, CCA on BSS2 is constant: -82 dBm
- Simulation duration: 100 s

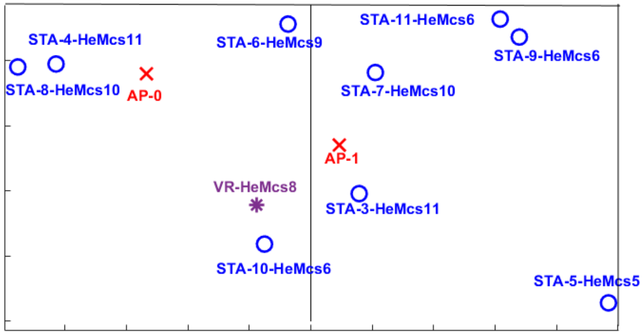
VR/AR TGax Scenario Simulation Examples

Three realizations: The nodes are distributed in the room with *different (x, y) axis corresponding to three cases*

- VR throughput >= 14.7 Mbps, HOL delay <= 5 ms
- Maximize the aggregated throughput

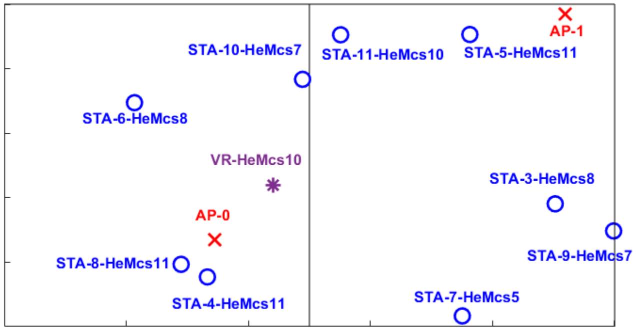
Realization 1

25 m x 25 m



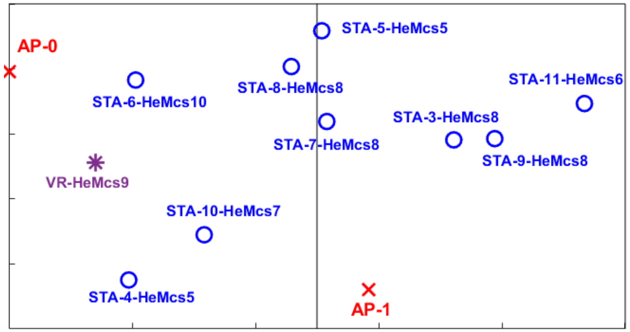
Realization 2

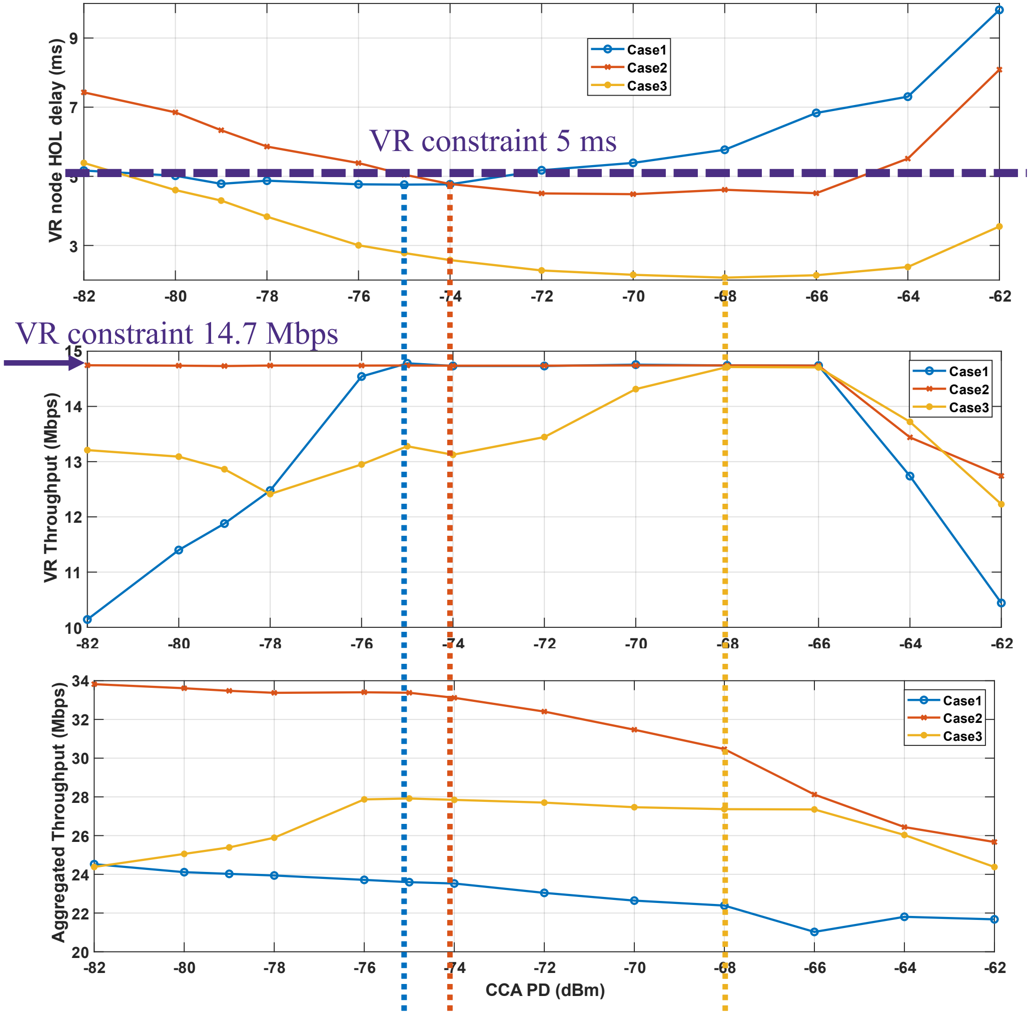
25 m x 25 m



Realization 3

25 m x 25 m





R1: -75 dBm **R2: -74 dBm** **R3: -68 dBm**

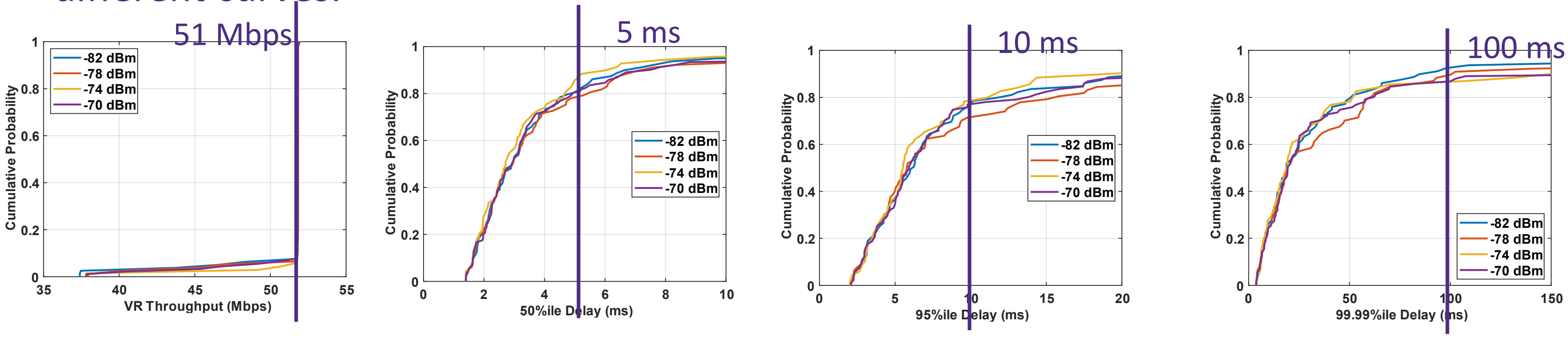
For different network topologies, we expect different 'optimal' CCA PD thresholds!

Can we use the deep reinforcement learning to learn from the environment and find the optimal CCA PD?

Simulation Results

Different realizations: Nodes distributed uniformly in room with *- 100 realizations*

Brute force the CCA-PD value in BSS-1 (VR) and other BSS kept fixed @ -82 dBm to draw different curves.



By choosing a constant CCA-PD regardless of the different locations (different realizations) cannot meet VR requirements.

For different network topologies, we may have different 'optimal' CCA PD thresholds! (As shown in the table for 2 example scenarios)

Table: Results over different CCA PD (dBm) for R1 and R2

Results	Realization	-82 dBm	-78 dBm	-74 dBm	-70 dBm
VR T'put (Mbps)	R1	51.82	51.82	51.82	51.82
	R2	51.82	51.82	51.82	51.82
VR 50%ile delay (ms)	R1	3.57	3.80	3.99	3.39
	R2	3.65	3.91	4.18	5.40
VR 95%ile delay (ms)	R1	7.88	9.25	11.50	7.44
	R2	6.88	6.26	9.27	18.60
VR 99.99%ile delay (ms)	R1	16.34	16.47	36.75	27.45
	R2	18.94	15.57	34.34	51.81
Agg-T'put (Mbps)	R1	72.14	72.24	72.01	73.36
	R2	81.49	78.47	78.47	78.48

Challenges and Motivation

Lessons learned from study

- \> Different Nodes locations per realization can impact the optimal CCA PD selection
  - Various levels of inter-BSS interferences
  - Need to balance hidden and exposed nodes for successful simultaneous transmissions

Limitations for the traditional optimization methods:

- \> Model/Algorithm depends on some assumptions
  - Known the locations of the nodes
  - Known the channel/pathloss models etc.
  - Same transmission power and CCA over all the nodes and BSSs

Complexity/challenges of real deployment scenarios:

- \> Transmission power may be different for APs and STAs
- \> No accurate location information
- \> Only partial information about channel/pathloss models
- \> Scalability: from 2D to 3D (including floors) , multiple BSSs (>2), power and CCA per node per BSS control (BSS coloring)-> hard to build analytical models for every case

Need to learn and adapt!

AI/ML (Deep Reinforcement Learning) Approaches:

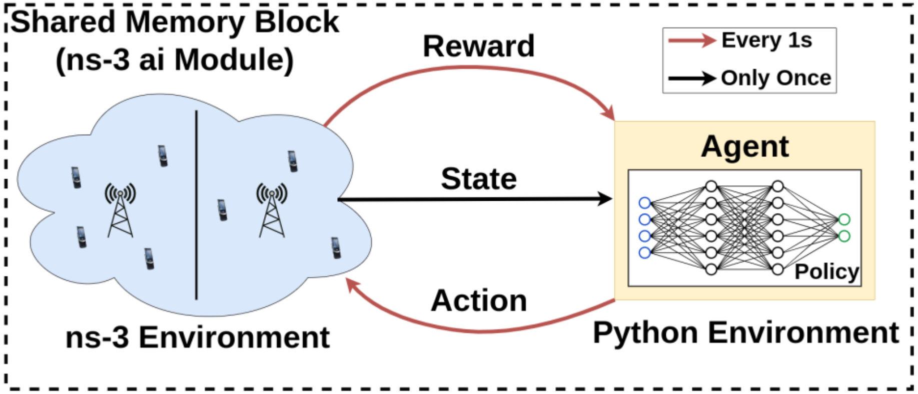
- \> Availability to learn from imperfect input and hidden properties
- \> Availability to learn from large amount of wireless data and maintain the memory

Example: Optimization with DRL and ns3-ai

State (Input): Rx Power and MCS of each node in the BSS-1:

- M: total nodes in the BSS 1, i.e., STA1, STA2, …., AP1
- N: total nodes in the whole network (BSS1+BSS2)

$$\begin{array}{cc} M & \begin{bmatrix} P_{rx}(0,0) & \cdots & P_{rx}(0,N), & MCS(0) \\ \vdots & \ddots & \vdots & \vdots \\ P_{rx}(M,0) & \cdots & P_{rx}(M,N), & MCS(M) \end{bmatrix} \\ & N+1 \end{array}$$



Action (Output): CCA PD Threshold for **BSS-1**

Reward*: Aggregated throughput, VR Throughput and delay

$$r_t = \alpha * Tpt + \beta * (T_{constraint} - Hol) + \eta * (Tpt_{required} - Tpt_{vr})$$

** For simplicity, we design this linear combination of throughput and delay. The α, β and η can be adjusted for the trade-off.*

Policy (Algorithm): Deep Q-learning: 2 fully connected layers with 64 neurons each layer

Training and testing:

- Using 500 realizations to train the DQN networks, i.e, DQN learns from this 500 different realizations
- Testing on 100 different realizations, i.e., DQN only outputs the CCA-PD based on the power measurement

App store for ns3-ai: https://apps.nsnam.org/app/ns3-ai/

Deep Q-Learning

Deep Q-learning is one algorithm of DRL algorithms with gradient methods:

- Simple and easy for start
- Good at handling the discrete action space
- Easy to generalize across similar states

Overview of DQN policy

> Objective: Maximize the accumulate reward from R_t

$$R_t = r_t + \gamma r_{t+1} + \gamma^2 r_{t+2} + \cdots$$

> Q-function/value: Expectation of accumulate reward for a given action and state

> Q-Learning: Choose the action with maximum Q-value for a given state

> Update rule:

$$Q(s, a) = \mathbb{E}[R_t]$$

We need approximation for the Q function – Deep neural networks

$$Q(s,a) \leftarrow \underbrace{Q(s,a)}_{\text{old value}} + \underbrace{\sigma}_{\substack{\text{learning}\\ \text{rate}}} [\underbrace{r'}_{\text{reward}} + \underbrace{\gamma}_{\substack{\text{discount}\\ \text{factor}}} \underbrace{\max_{a'} Q(s',a')}_{\text{expected optimal value}} - \underbrace{Q(s,a)}_{\text{old value}}]$$

Typical setups: $\sigma = 1e^{-4}, \gamma = 0.99$

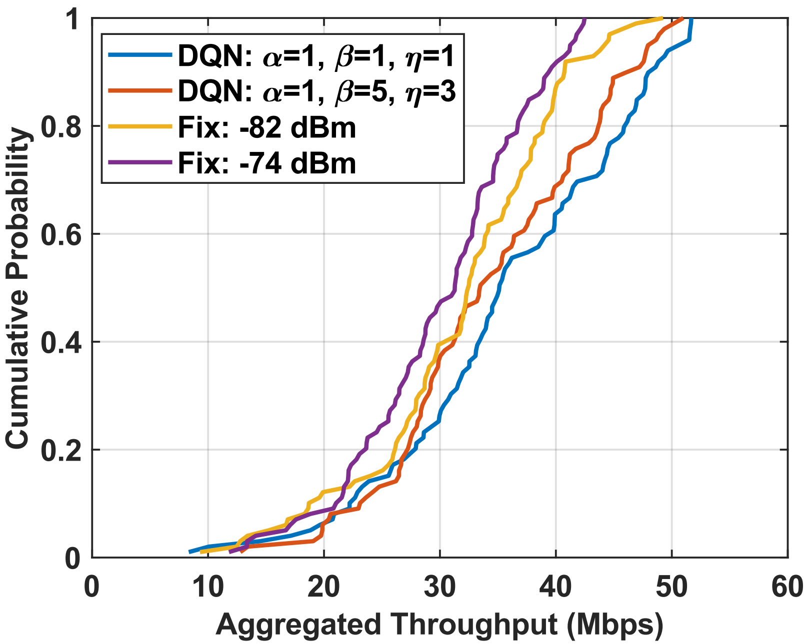
Results – 2 BSSs

Table: VR traffic fulfill percentage: VR throughput >= 14.7 Mbps, HOL delay <= 5 ms

Target	Fix: -82	Fix: -78	Fix: -74	Fix: -70	Fix: -68	DQN:$\alpha = 1, \beta = 1, \eta = 1$	DQN:$\alpha = 1, \beta = 5, \eta = 3$
VR Delay	74%	76%	85%	81%	75%	88%	94%
VR Throughput	56%	64%	68%	74%	62%	84%	93%

Fix CCA-PD threshold

DQN algorithm



Results for 100 realizations

- DQN algorithm is trained on other 500 different realizations
- DQN only output the CCA-PD based on the states, no online training while testing
- DQN can meet most of the VR requirements while maximizing the aggregated throughput
- Missing cases can't meet the requirements by simply changing CCA, e.g., have low VR MCSs and close to interferences

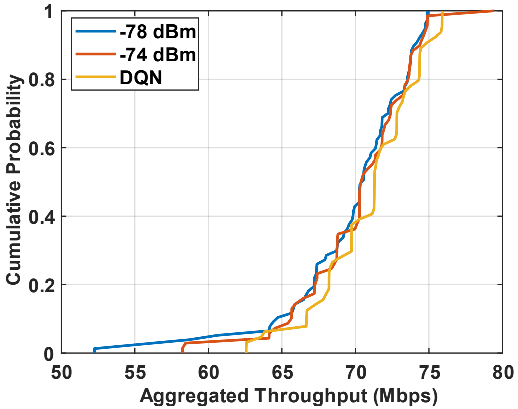
For different parameters in the reward design:

- Issue: artificially choose the parameters
- With larger β and η, larger punishment for missing the VR constraint -> lower aggregated t'put but higher fulfilling rates

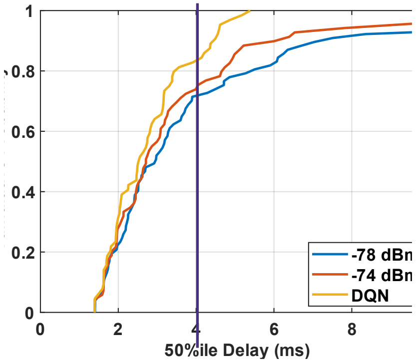
Reward: Aggregated throughput, VR Throughput and delay

$$r_t = \alpha * Tpt + \beta * (T_{constraint} - Hol) + \eta * (Tpt_{required} - Tpt_{vr})$$

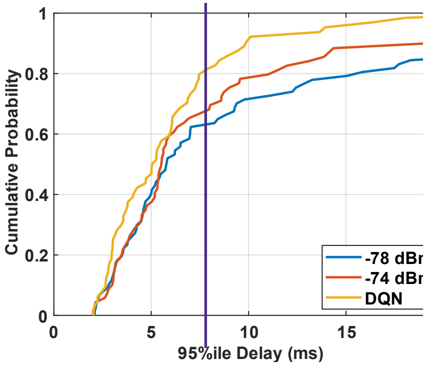
Results – 4 BSSs



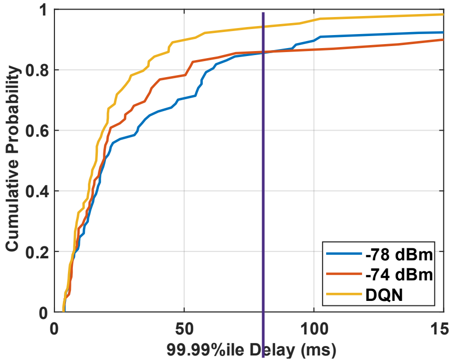
5 ms, DQN 98% meet



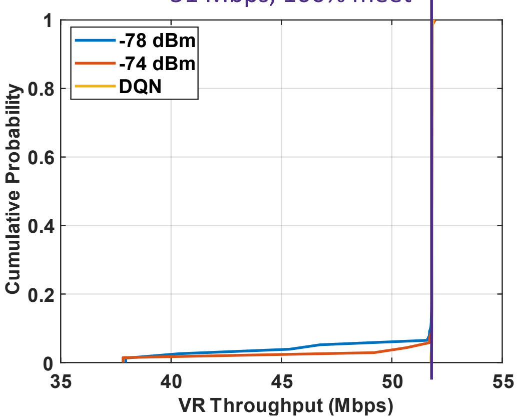
10 ms, DQN 92% meet



100 ms, DQN 96% meet



51 Mbps, 100% meet



Results for 100 new realizations

- DQN algorithm is trained on other 500 realizations
- DQN only output the CCA-PD based on the states, no online training while testing
- DQN can meet most of the VR requirements while maximizing the aggregated throughput
- Missing cases can't meet the requirements by simply changing CCA, e.g., have low VR MCSs and close to interferences, so we need to consider other methods:
    - -802.11be Multi-link operation
    - -AP coordination

Reward: Aggregated throughput, VR Throughput and delay

$$r_t = \alpha * Tpt + \beta * (T_{constraint} - Hol) + \eta * (Tpt_{required} - Tpt_{vr}), \alpha = 1, \beta = 5, \eta = 3, T_{constraint} = 5$$

Simulation study for Multi-BSSs

> **Lessons Learned from Previous Study:**

- Node location variations can significantly impact the optimal CCA PD selection.
- Inter-BSS interferences exist at various intensities.
- It's crucial to balance hidden and exposed nodes to allow for simultaneous successful transmissions.

> **As we scale from two BSSs to multiple BSSs**

- Growing complexity with:
  - More interference for different setups: Node location and traffic variations.
  - Varying power and CCA for different BSSs.
- As the number of BSSs increases, building accurate analytical models for every possible scenario becomes even more challenging:
  - Often faced with imperfect inputs, e.g., inaccurate node locations.
  - Only partial knowledge of channel/pathloss models is available.

Benefits of AI/ML algorithms

> **Limitations of Traditional Optimization Methods:**

- Dependence on certain assumptions, such as:
  - Precise node locations
  - Specific channel/pathloss models
- Need additional assumptions:
  - Uniform transmission power and CCA across all nodes and BSSs.
  - Symmetry topology setups

> **Deep Reinforcement Learning (DRL) Benefits:**

- By exploring the DQN algorithm as an example, we can see with dynamically adjusting the CCA-PD, it has much better satisfaction rate for the VR/AR traffic
  - Capability to learn from imperfect and incomplete data.
  - Ability to grasp hidden attributes and trends.
  - Efficiently processes vast amounts of wireless data and retains crucial information.

Future Work

- **Explore BSS coloring and spatial reuse based on 802.11ax standard**
  - Validation the throughput of Channel bonding [6]
    - Two BSSs, 20+20 MHz channel, partially overlapping
    - Using the analysis from [6] to predict the throughput
  - Validation the BSS coloring and OBSS PD [7]
    - Two BSSs, 20+20 MHz channel, fully overlapping or partially overlapping
    - Using the analysis from [7] to predict the throughput

- **Explore multi-link operation (MLO) in 802.11be**
  - Propose new models to validate the throughput and HOL delays in MLO
  - Scheduling and resource allocation problems in MLO

[6] L. Lanante and S. Roy, "Analysis and Optimization of Channel Bonding in Dense IEEE 802.11 WLANs," in IEEE Transactions on Wireless Communications, vol. 20, no. 3, pp. 2150-2160, March 2021, doi: 10.1109/TWC.2020.3041956.

[7] L. Lanante and S. Roy, "Performance Analysis of the IEEE 802.11ax OBSS_PD-Based Spatial Reuse," in IEEE/ACM Transactions on Networking, vol. 30, no. 2, pp. 616-628, April 2022, doi: 10.1109/TNET.2021.3117816.

BSS Coloring and Spatial Reuse in 802.11 ax

AP and clients can differentiate between intra-BSS frames and OBSS frames via use of BSS Color bits

- Higher OBSS-PD value leads to more simultaneous transmissions, but potentially lowers SINR
- Goal: increase spatial reuse, while not causing a significant reduction to selected MCS due to interference

Adaptive OBSS-PD

- 802.11 signal detect and TXPWR threshold may be adjusted dynamically by both AP and clients

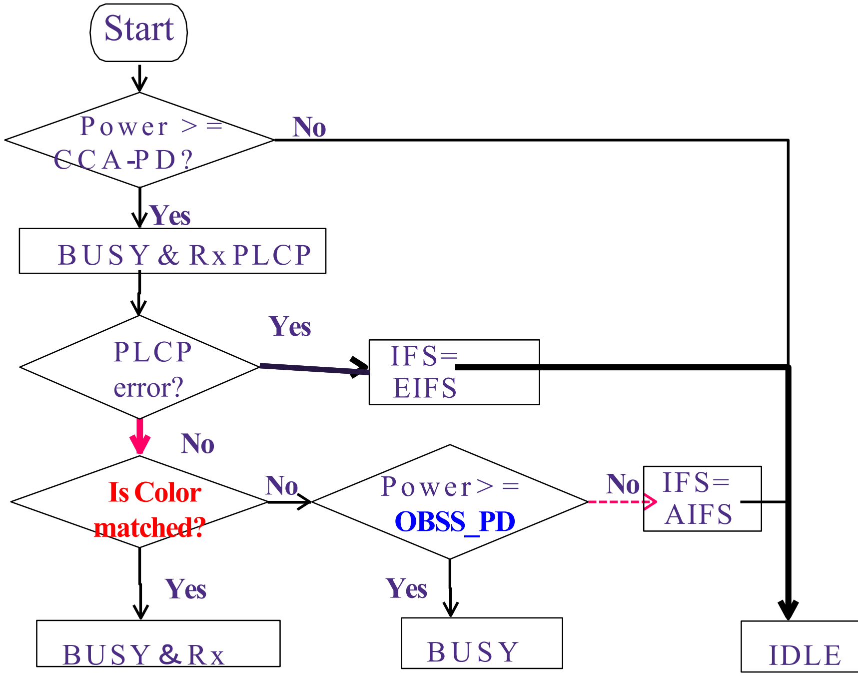


Fig. CCA with BSS Coloring and OBSS_PD

Work[*] develops an analytical model for IEEE 802.11ax spatial reuse that provides useful rules for optimizing network area throughput.

[*] L. Lanante and S. Roy, "Performance Analysis of the IEEE 802.11ax OBSS_PD-Based Spatial Reuse," in IEEE/ACM Transactions on Networking, vol. 30, no. 2, pp. 616-628, April 2022, doi: 10.1109/TNET.2021.3117816.

Backup

ns-3 Open Source Network Simulator

❑ **Layer-2 Packet-in/Packet-out Simulator for Wireless Networks (WiFi, 4G/5G)**

- ns-3 homepage: www.nsnam.org
- User group: ns3w-group@googlegroups.com

- ns-3 consortium: https://www.nsnam.org/consortium/about/

❖ collection of organizations cooperating to support continued development of new ns-3 user modules

❑ Operates in support of the open-source project: managed by UW, INRIA founder-member

- Meeting place for inputs/guidance between industrial members and ns-3 developers on next-gen needs and gaps
- provides maintenance support for ns-3 models
- supporting administrative activities necessary (Annual ns-3 mtg, website, user groups ..)

Short History

- Ns-3 simulator developed over 2005-2014 via 2 successive NSF CRI awards https://www.nsf.gov/pubs/2015/nsf15590/nsf15590.htm
  - NSF Awards
    (06-10) ``Developing Next-Generation Open-Source Network Simulator”
    (10-15) ``Frameworks for ns-3”
    (12-15) ``Achieving Realism in ns-3 Wireless Network Simulation“
    (18-20) ``Performance Evaluation of Advanced Wireless Networks Edge Infrastructure: Network Simulation and Test Beds”
    (20-24) ``ns-3 Network Simulation for Next-G Wireless”
  - NIST
    (18-22) `` Cross-Layer Modeling & Performance Evaluation of 5G Public Safety based on NR C-V2X Sidelink"
- Constant effort to close gap between new standards-based wireless protocol stack enhancements and ns-3 implementation !!

ns-3
NETWORK SIMULATOR

Impact

- **SIGCOMM Networking Systems Award 2020** ``recognize the development of a networking system that has had a significant impact on the world of computer networking”

  - the ns family of network simulators (ns-1, ns-2, and ns-3)

https://www.sigcomm.org/content/sigcomm-networking-systems-award

Code statistics in a typical year (July 21-Jun22)

- **176 commits** by **39 authors**
- **159,000 lines** of C++ code added/deleted (ns-3-dev)
  - parsed output of git diff --stat filtered for .{cc,h}
  - 114,000 lines due to wifi module and wireless examples
- **330 Merge Requests** opened
- **196 Issues** filed

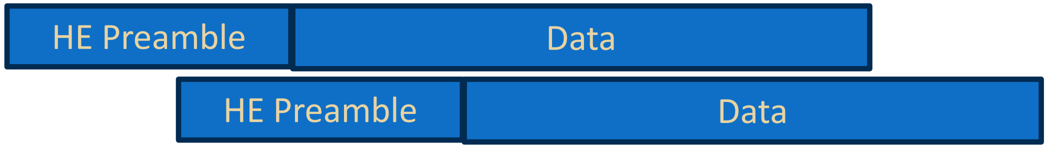
Small set of active maintainers (5-7) at any given time doing most work

Much of the maintenance/review work is done on maintainers' free time

Difficult to devote time to outreach, long-term software issues, reducing technical debt, improving ease of use, tracking standards, etc.

Rx Decoding Summary (2)

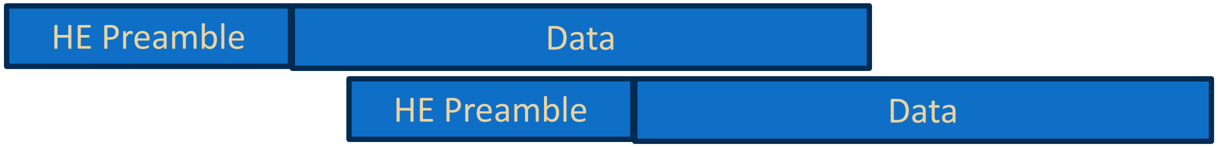
1. Multiple BSSs and not everyone can hear each other
   - **Asynchronous Collisions During HE Preamble**: Collisions due to nodes outside of CCA range. Collision occurs after first 4 us of the signal reception and before the end of HE preamble (36 us)



HE Preamble | Data

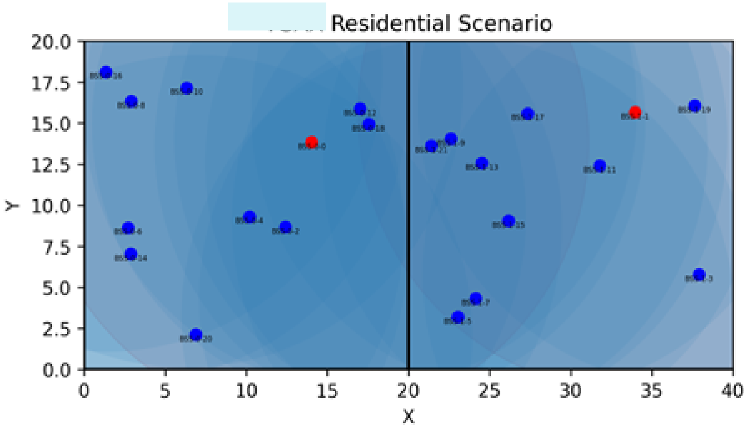
HE Preamble | Data

   - **Asynchronous Collisions During Payload**: Collisions due to nodes outside of CCA range. Collision occurs after HE preamble (36 us). CRC fail



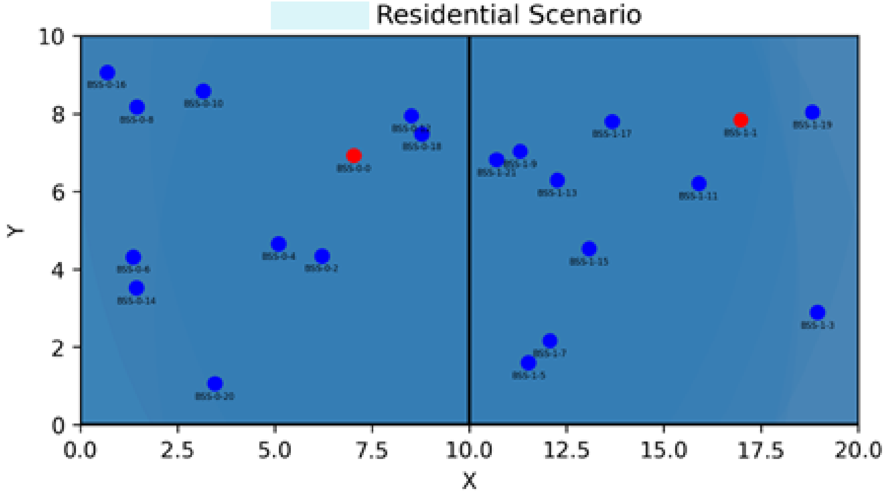
HE Preamble | Data

HE Preamble | Data



Rx Decoding Summary (1)

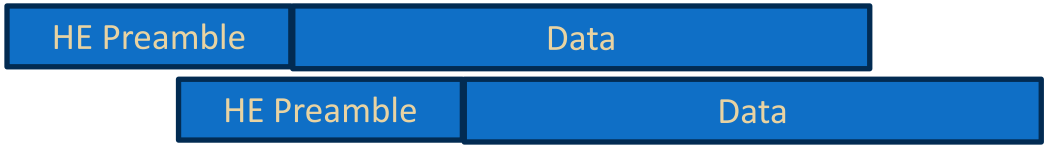
1. Single node transmission:
   - **No Drop**
2. Multiple STAs/BSSs and everyone can hear each other
   - **Synchronous Collision During Preamble**: Collisions due to same backoff window count. Drop occurs in the first 4 us of HE preamble



More details in the backup slides

Rx Decoding Summary (2)

1. Multiple BSSs and not everyone can hear each other
   - **Asynchronous Collisions During HE Preamble**: Collisions due to nodes outside of CCA range. Collision occurs after first 4 us of the signal reception and before the end of HE preamble (36 us)



   - **Asynchronous Collisions During Payload**: Collisions due to nodes outside of CCA range. Collision occurs after HE preamble (36 us). CRC fail