Multi BSS Wi-Fi Simulations in ns-3

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Outline

Ia. Throughput analysis and validation

Ib. Delay analysis and validation

II. CCA Threshold Optimization

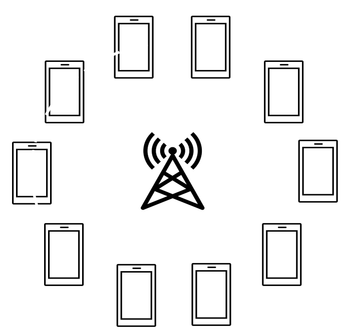
- Analysis the impact of CCA
- 802.11 TGax Simulations
- CCA Optimization with ns3-ai

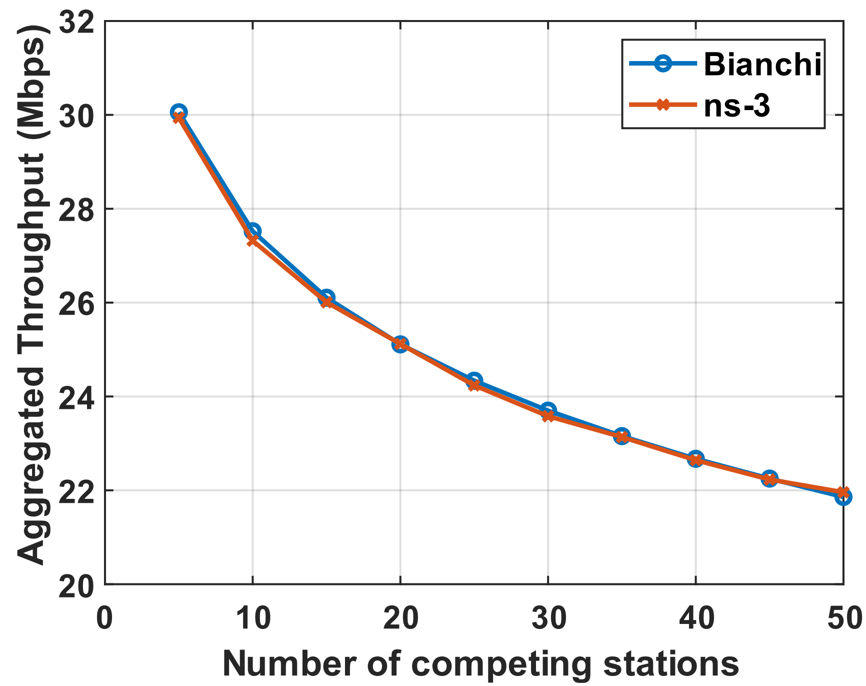
I. Throughput Analysis

- Benchmark DCF model under saturated traffic, single BSS: Bianchi [1]
- ns-3 simulations (src/wifi/examples/wifi-bianchi.cc) used to validate simulator against analysis (as WiFi standard evolved)

- Results for 802.11ax: 5 to 50 nodes, infrastructure networks, MCS4

❑ STAs uniformly distributed on a circle;
❑ No successful multiple Txmissions!

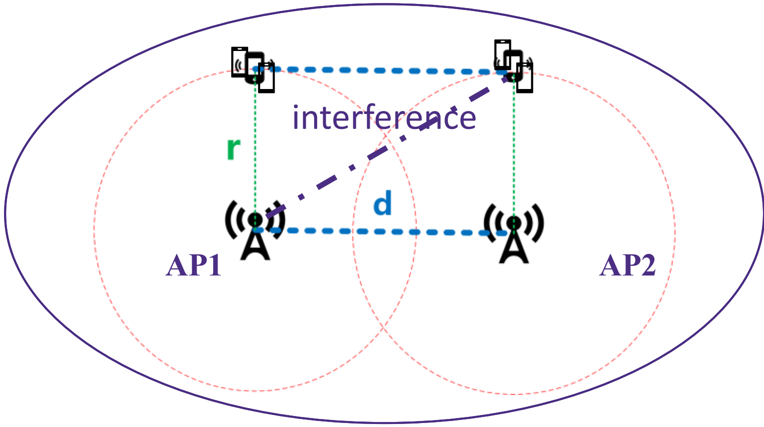




[1] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," in *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535-547, March 2000

Throughput – Multi-BSS analysis

Axis:
AP1 (0, 0) AP2 (d, 0)
STAs (0, r) STAs (d, r)



CCA Range = 30 m

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

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

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

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

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

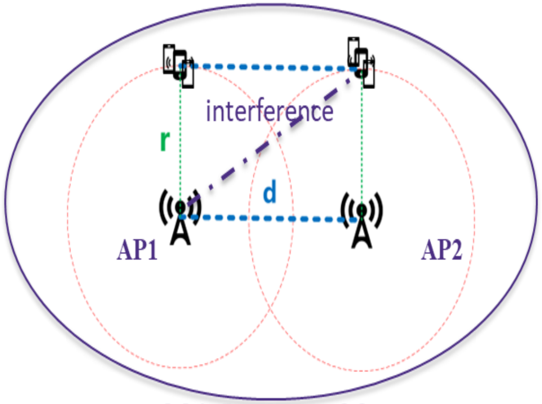
SINR required for PER, packet size 1500 bytes

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

[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



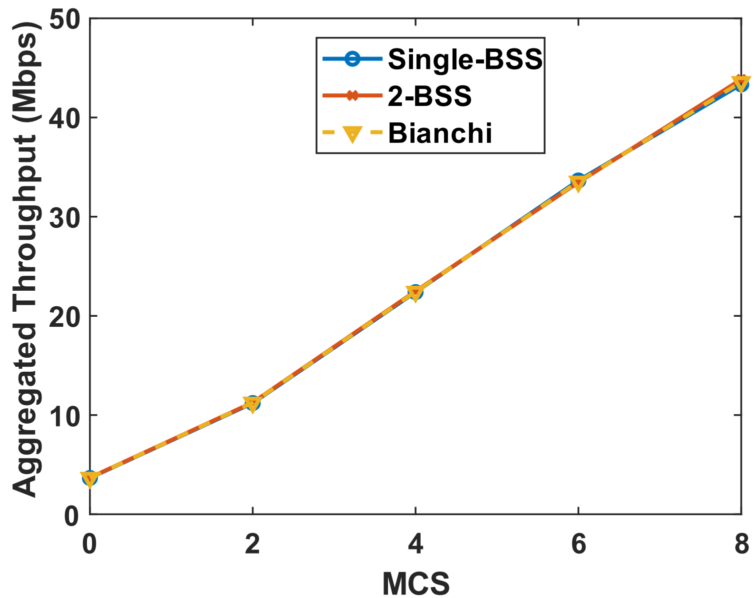
CCA Range = 30 m

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:

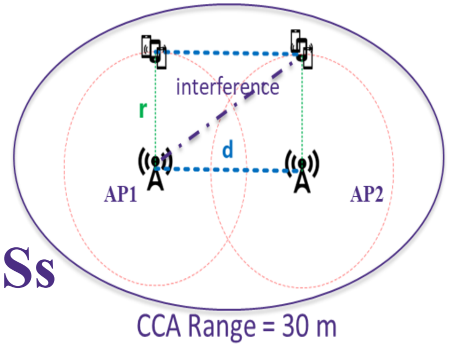
Parameters	Value
P_{rx}	-61.6 dBm
P_{in}	-64.6 dBm
Noise	-128 dBm
SINR	2 dB



- Results validated against Bianchi model predictions

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

Throughput – Multi-BSS analysis

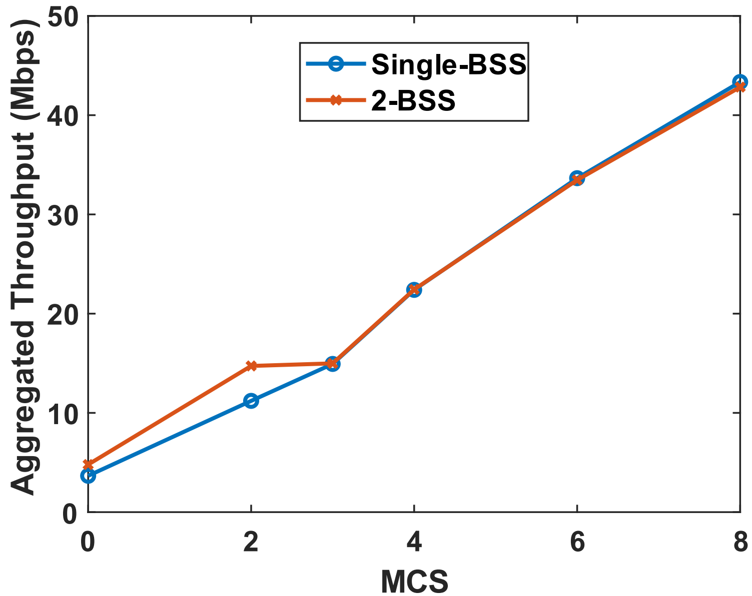


Case 2: Successful Simultaneous transmission @ low MCSs

- Setup: Total 50 STAs (25 STAs in each BSS)
  - $r = 10m$, $d = 20m$, $\sqrt{r^2 + d^2} = 22.3m$, 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

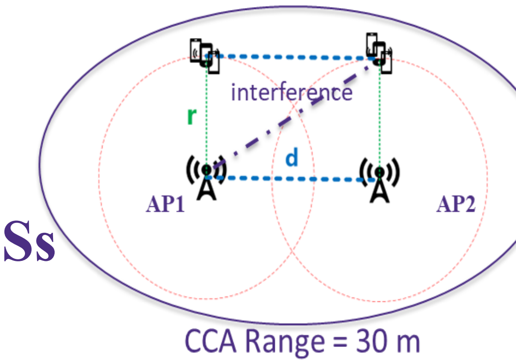
❖ Results:

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

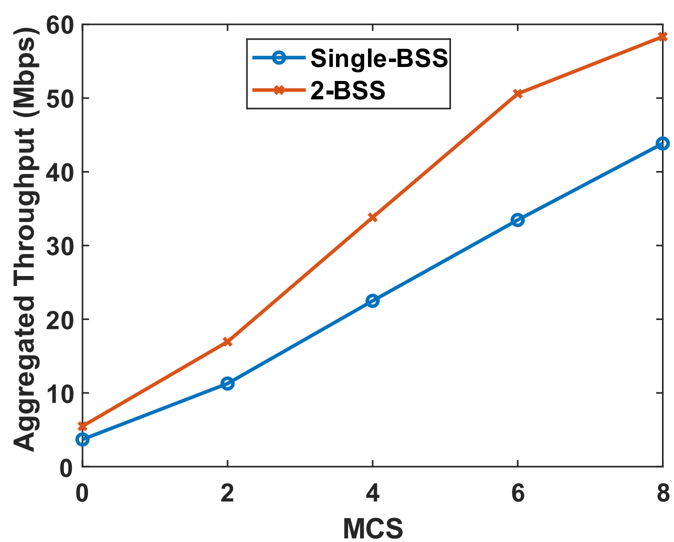


Case 3: Successful Simultaneous transmission @ all MCSs

- 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



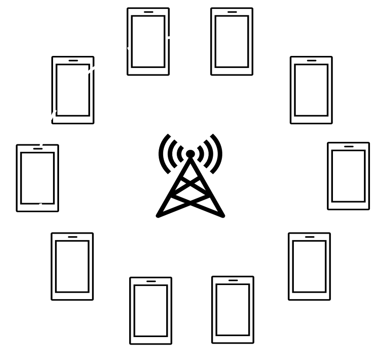
- Simultaneous transmission happens for all MCSs → multi-BSS throughput is UNIFORMLY larger
- Large single BSS throughput validated against the Bianchi model (similar to Case 1)

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**)

II. Delay Analysis

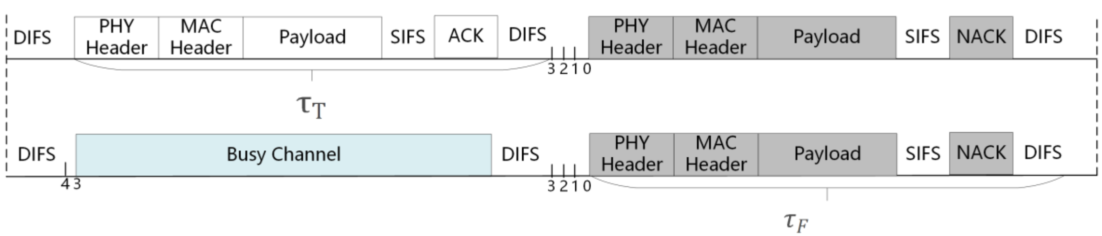
Simulation Topology

- AP: Center of circle
- STAs: Evenly spaced on the circle
- STAs are transmitting with a fixed MCS



Traffic Model

- UL Only traffic
- Each STA have Bernoulli arrivals with rate λ, i.e., each STA has probability λ to generate a new packet every τ_T time [3].
- τ_T time is the channel holding time at MAC layer for each frame



$Bernoulli\left(\frac{\lambda}{\tau_T}\right)$:

$\hat{\lambda} = n\,\lambda$, the aggregate input data rate for n nodes

[3] L. Dai and X. Sun, "A Unified Analysis of IEEE 802.11 DCF Networks: Stability, Throughput, and Delay," in IEEE Transactions on Mobile Computing, vol. 12, no. 8, pp. 1558-1572, Aug. 2013, doi: 10.1109/TMC.2012.128.

Delay Analysis - Simulation Cases

Delay Components in ns-3

1. **Queueing Delay**: difference between time instant when packet enters queue till it becomes Head of Line (HOL)
2. **DCF Back Off Delay** (difference between time instant when it becomes HOL to 1st transmission)
3. **Transmission Delay** (difference between 1st transmission instant till when packet is de-queued from TX Buffer)

* Validated the delay components **(2+3)** in ns-3 as defined in analytical model [3]

Cases	Scale by number of STAs	Scale by initial CW
Saturated: $\hat{\lambda} = 1$, time=30s	n=[5,…,50][1] w=15 k=6	n=15 w=[15,…,1023][2] k=6
Unsaturated: $\hat{\lambda} = 0.15$, time=200s	n=[5,…,50][1] w=15 k=6	n=15 w=[15,…,1023][2] k=6

$\hat{\lambda}$ = aggregate input rate, proportional to Bernoulli arrival probability;
n = number of STAs; w = initial CW; k = backoff stages.

[1] Step size = 5
[2] Powers of 2 from 2^4 to 2^{10}

[3] L. Dai and X. Sun, "A Unified Analysis of IEEE 802.11 DCF Networks: Stability, Throughput, and Delay," in IEEE Transactions on Mobile Computing, vol. 12, no. 8, pp. 1558-1572, Aug. 2013, doi: 10.1109/TMC.2012.128.

Delay Validation - Analytical Model

Access Delay:

- Saturated Case
  - Mean delay

Stable State from Markov chain for backoff window change due to collisions

Success

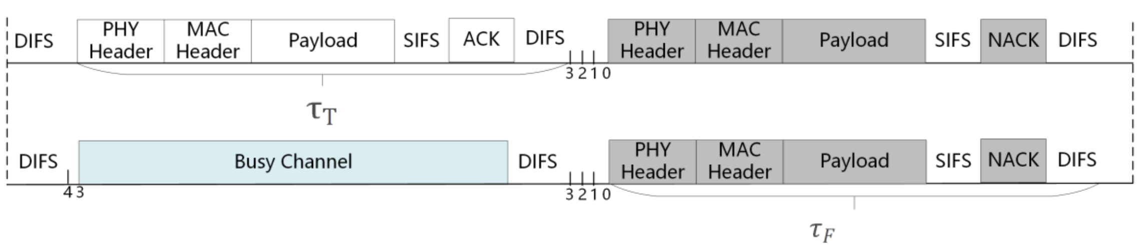
$$E[D_0] = G'_{D_0}(1) = \tau_T + \frac{1-p}{p}\tau_F + \frac{1}{\alpha}\cdot\left(\frac{1}{2p} + \frac{W}{2}\left(\frac{1}{1-\frac{1-p}{q}} + \left(\frac{1}{p} - \frac{1}{1-\frac{1-p}{q}}\right)\cdot\left(\frac{1-p}{q}\right)^K\right)\right)$$

Failure

- Unsaturated Case: e.g., with fixed $\hat{\lambda} = n\,\lambda = 0.15$, the aggregate input data rate for n nodes
  - Mean delay $E[D_{0,p=p_L}] \approx \tau_T + \frac{1+W}{2}$

Delay mainly related to the initial backoff window size with low arrival rate and low collision probability.

τ_T/ τ_F = channel holding time of successful/failed transmission;
p = probability of successful transmission of HOL packet given that the channel is idle;
W = initial backoff window size;
K = cutoff phase;
q = 2 for the exponential backoff;
$\alpha = \frac{1}{1+\tau_F-\tau_F*p-(\tau_T-\tau_F)*p*\ln p}$.

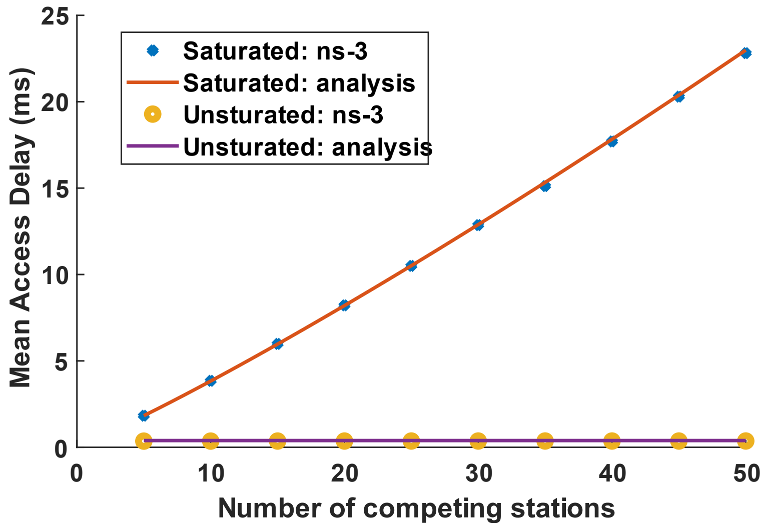


[3] L. Dai and X. Sun, "A Unified Analysis of IEEE 802.11 DCF Networks: Stability, Throughput, and Delay," in IEEE Transactions on Mobile Computing, vol. 12, no. 8, pp. 1558-1572, Aug. 2013, doi: 10.1109/TMC.2012.128.

More details - see backup slides

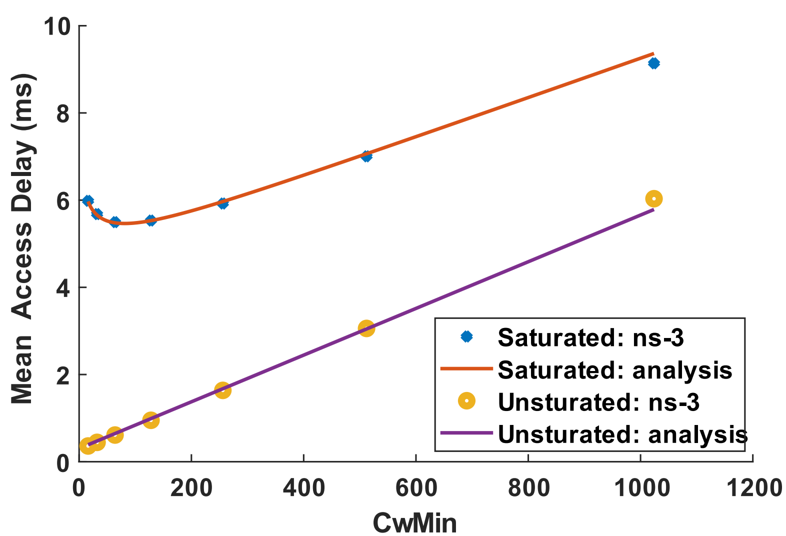
Delay Analysis

- 802.11ax, CwMin=16, CwMax = 2^6*CwMin, DCF Basic, Scale by number of STAs, MCS6



- ns-3 simulation results aligned with analytical model
- Under **Saturated** condition: delay scaled with node numbers → more nodes, more collisions
- Under **Unsaturated** condition: delay is constant → with fixed aggregate rate, low collisions

- 802.11ax, nSTA = 15, CwMax = 2^6*CwMin , DCF Basic, Scale by initial CW (CwMin) , MCS6



- ns-3 simulation results aligned with analytical model
- Under **Saturated** condition: delay first drops then increase → the tradeoff between less collisions and long backoff period
- Under **Unsaturated** condition, delay increases with CwMin → only related to the initial CW size

III. CCA Threshold Optimization

Clear Channel Assessment (CCA) Introduction

CCA-Energy Detect (CCA-ED)

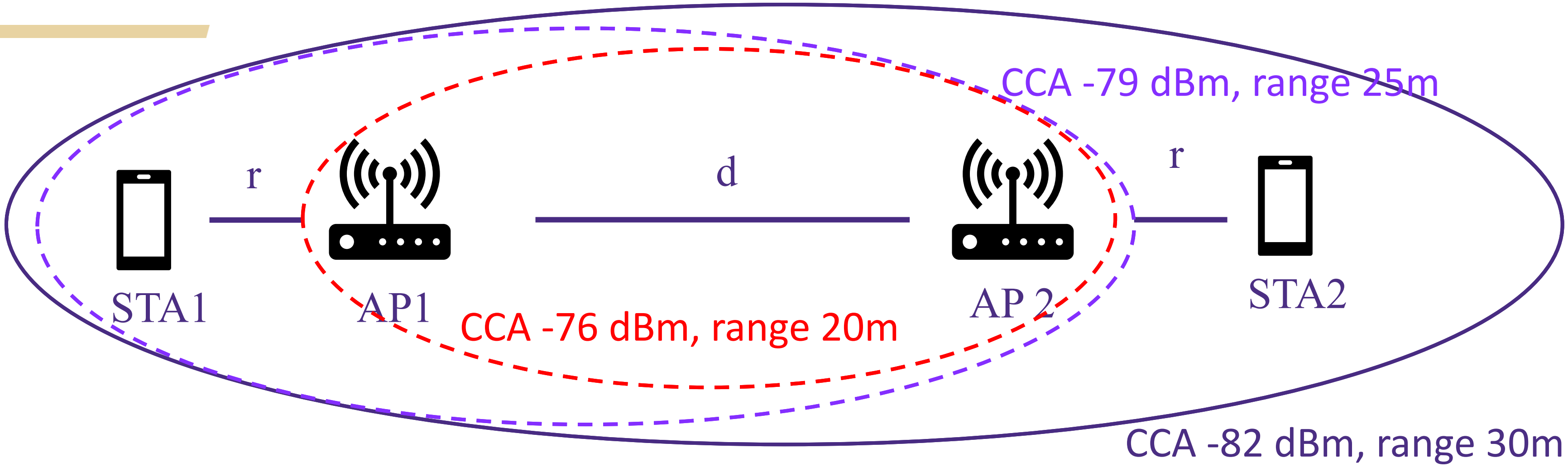
- Detect other (non-Wi-Fi) RF transmissions during the clear channel assessment (CCA).
- ED threshold is 20 dB higher than the signal detect threshold

CCA-Preamble Detect (CCA-PD)

- PD is used to identify any 802.11 preamble transmissions from another transmitting 802.11 radio
- Decode the preamble to get time information

→ consider CCA-PD threshold subsequently since there is no external RF in the simulations.

Changing CCA: Simple two 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

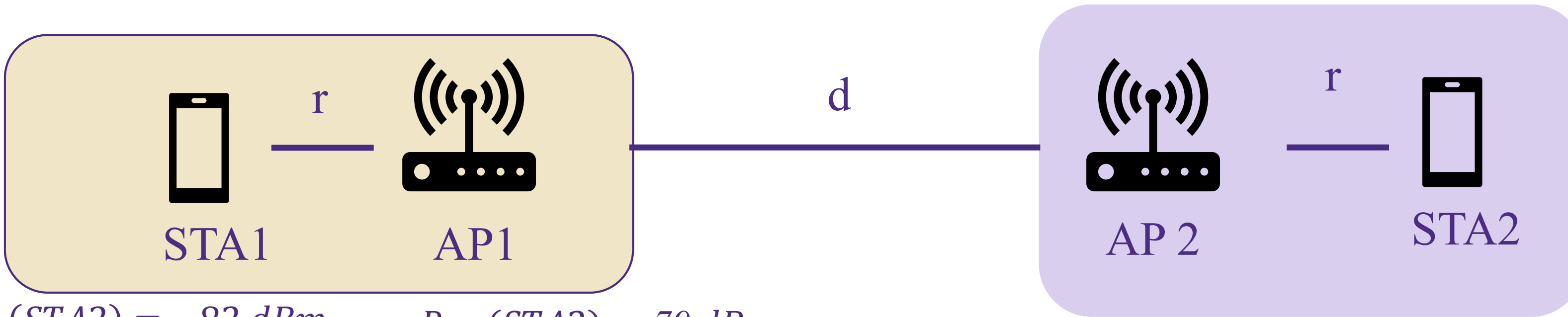
$$PL(dis) = L_0 + 10 * n * \log_{10}(\frac{dis}{d_0})$$

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)

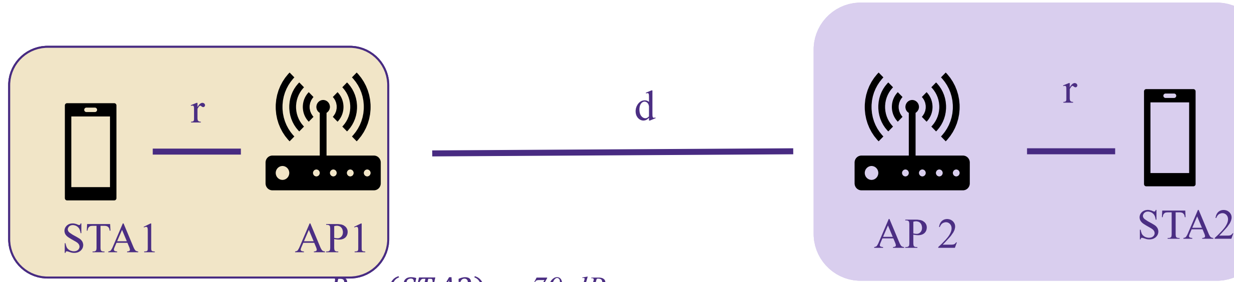
Packet error rate for different MCSs and SINR

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

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

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

Simulation Results



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

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

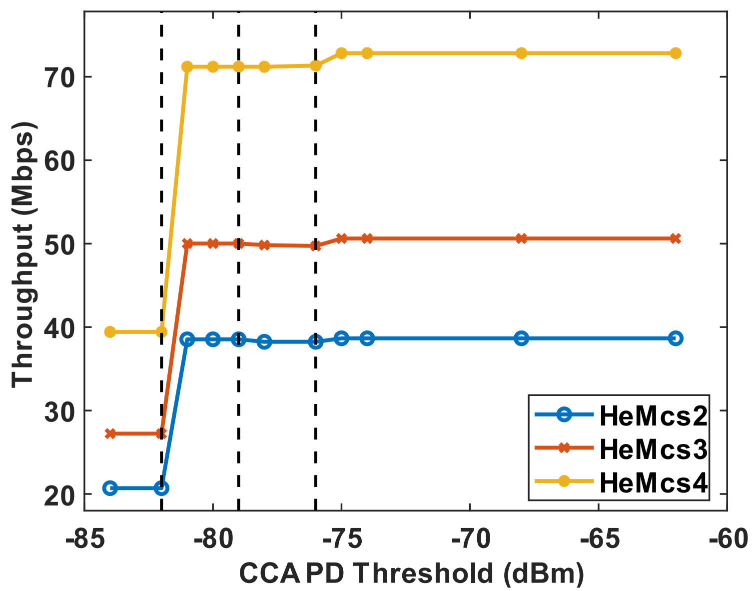
$P_{rx1}(STA2) = -79\ dBm$

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

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

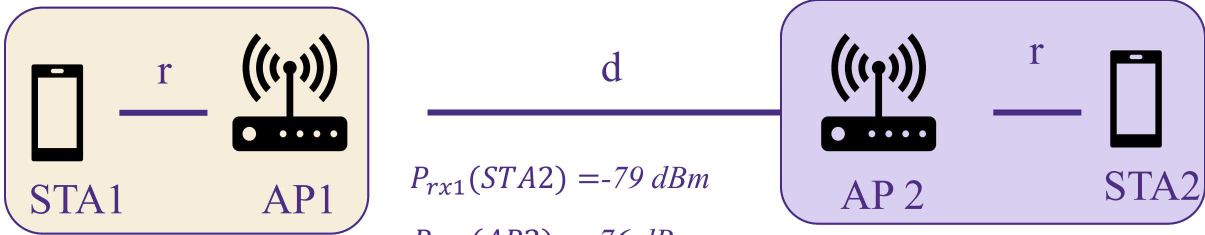
Packet error rate for different MCSs and SINR



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



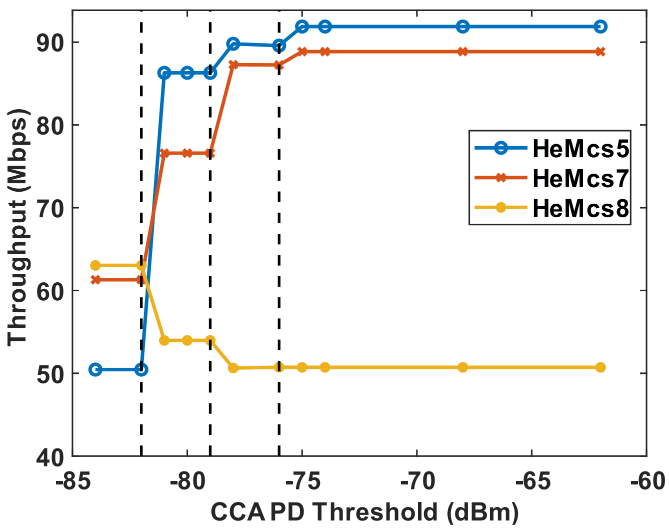
$P_{rx1}(STA2) = -82\ dbm$

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

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

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

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



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

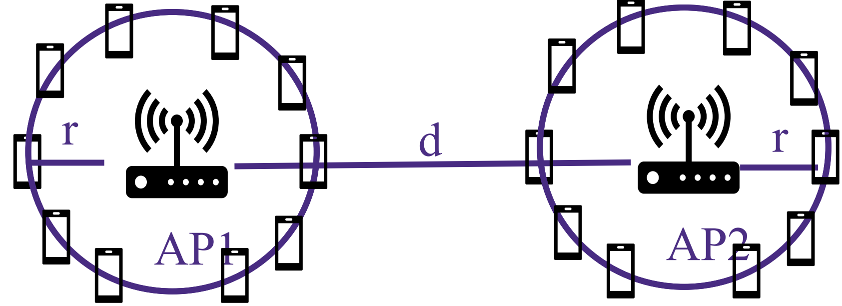
MCS	Single BSS	CCA <= -82	CCA > -76	2*Single BSS
5	46.3	50.4	91.9	92.6
7	51.4	61.2	88.9	102.8
8	56.1	63.0	50.7	112.2

- 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

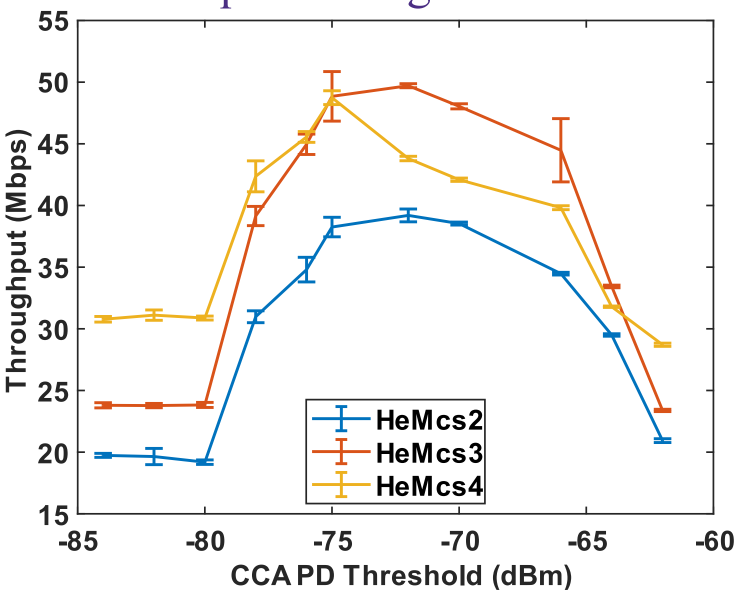


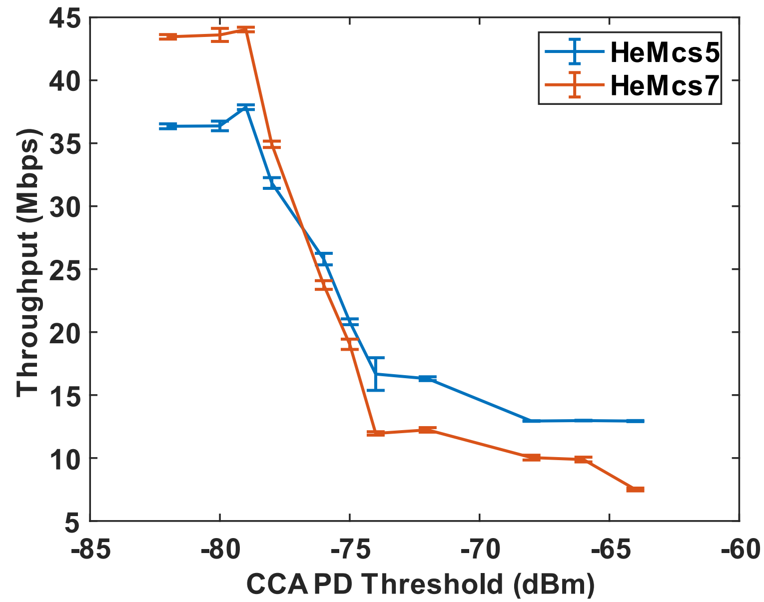
More stations (nSTA = 10), distributed on a circle, r = 5m, d = 20m, P_tx = 20 dBm:

→ 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



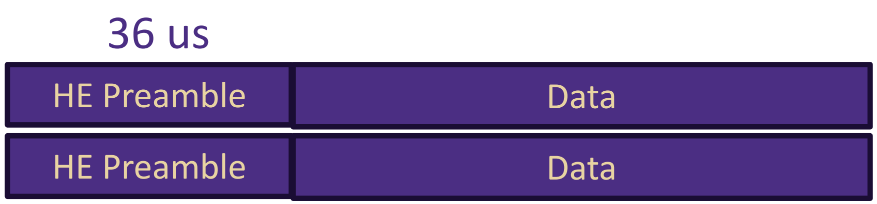


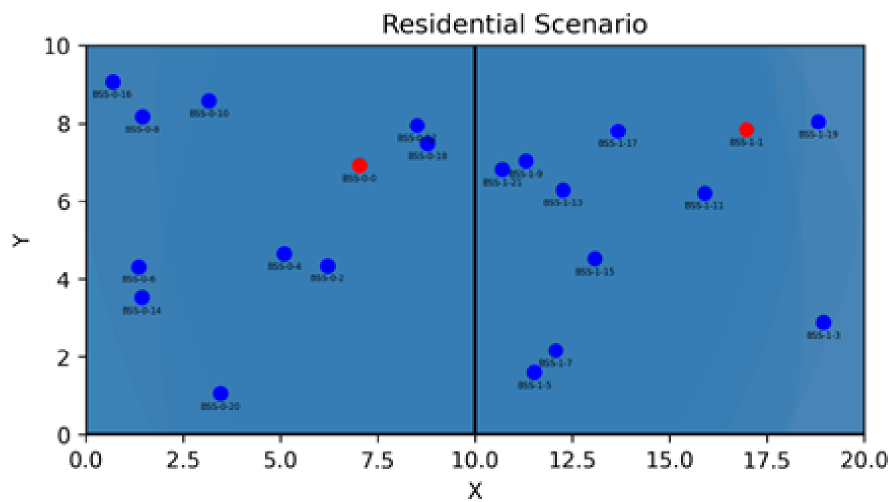
Analysis in [4] to find the optimal CCA threshold for a homogeneous network with constant link distances.

[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.

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

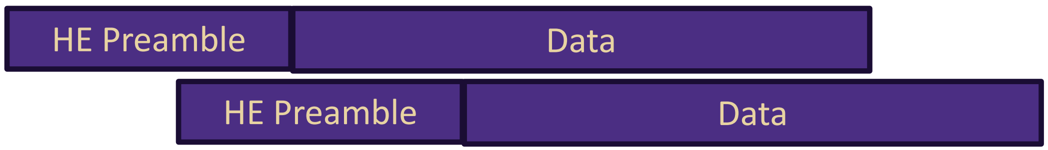




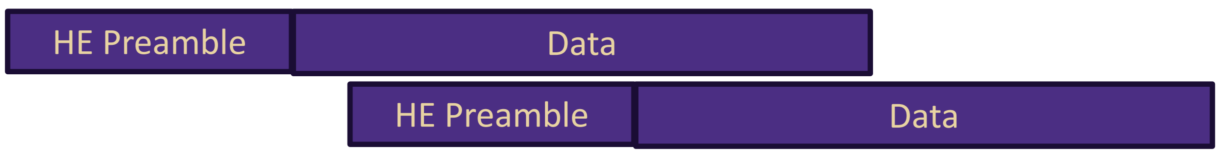
More details in the backup slides

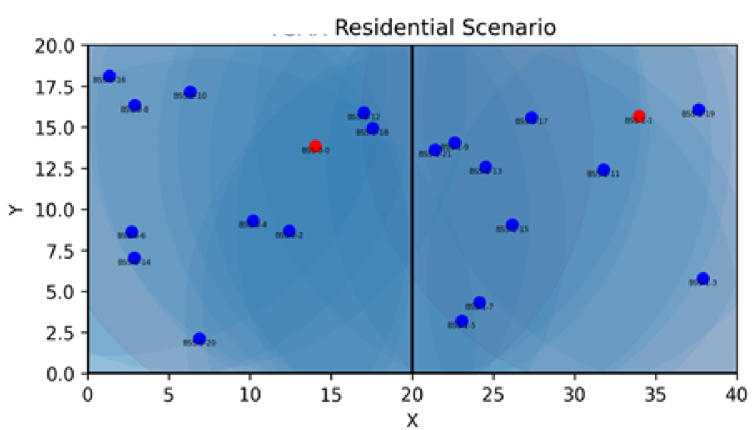
Rx Decoding Summary (2)

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)

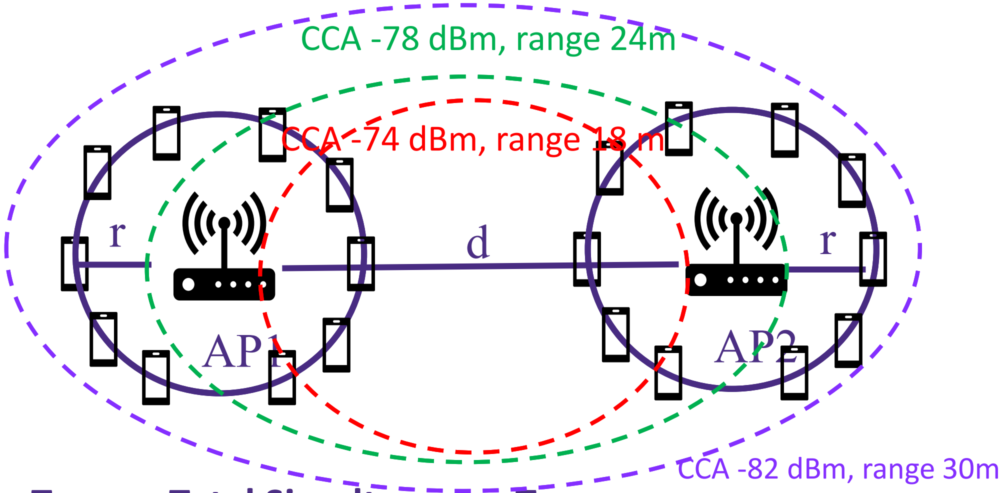


   - **Asynchronous Collisions During Payload**: Collisions due to nodes outside of CCA range. Collision occurs after HE preamble (36 us). CRC fail





ns-3 Labels: 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

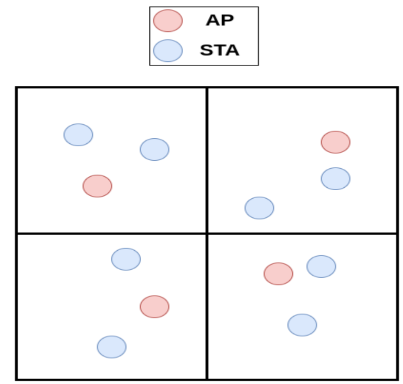
AMPDU disabled

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 Sim ult 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:

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

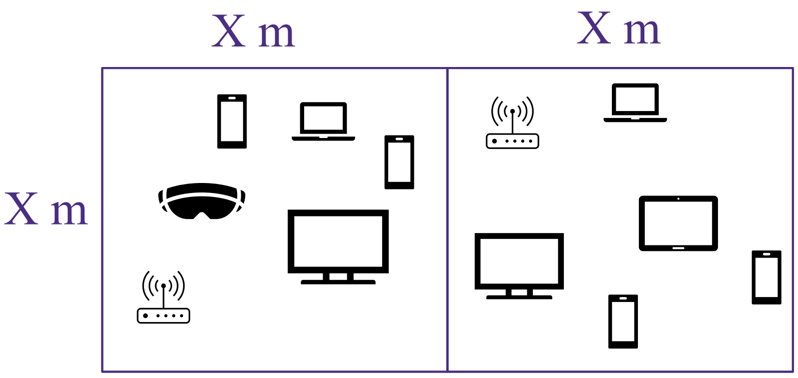
- Consider ***mixed traffic types***
  - VR/AR burst traffic: ns-3 VR traffic model [5]
  - CBR traffic as background

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

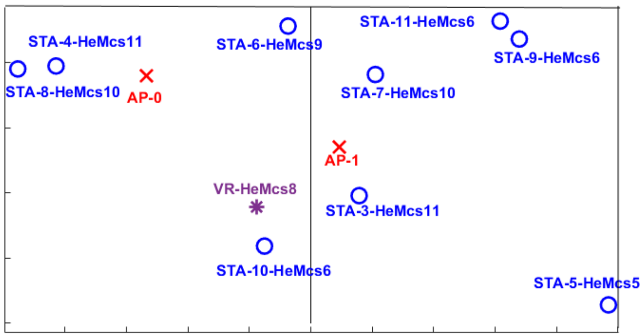
VR/AR TGax Scenario Simulation Examples

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

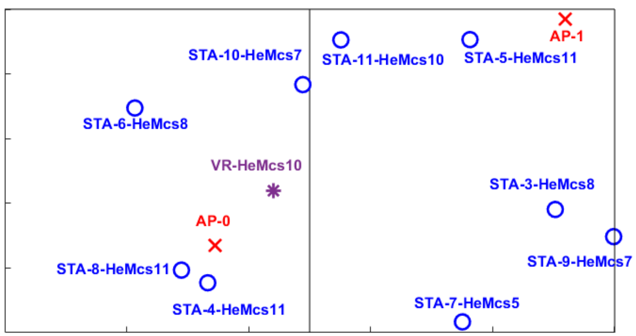
Realization 1

25 m x 25 m



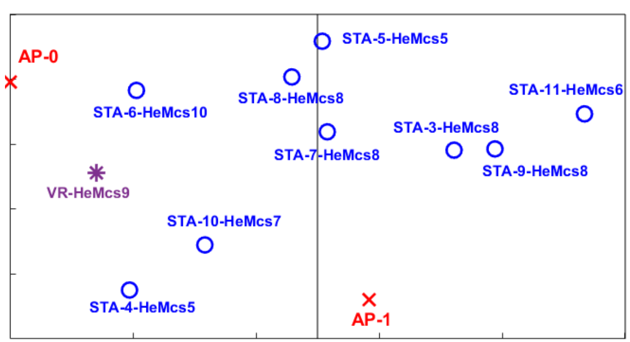
Realization 2

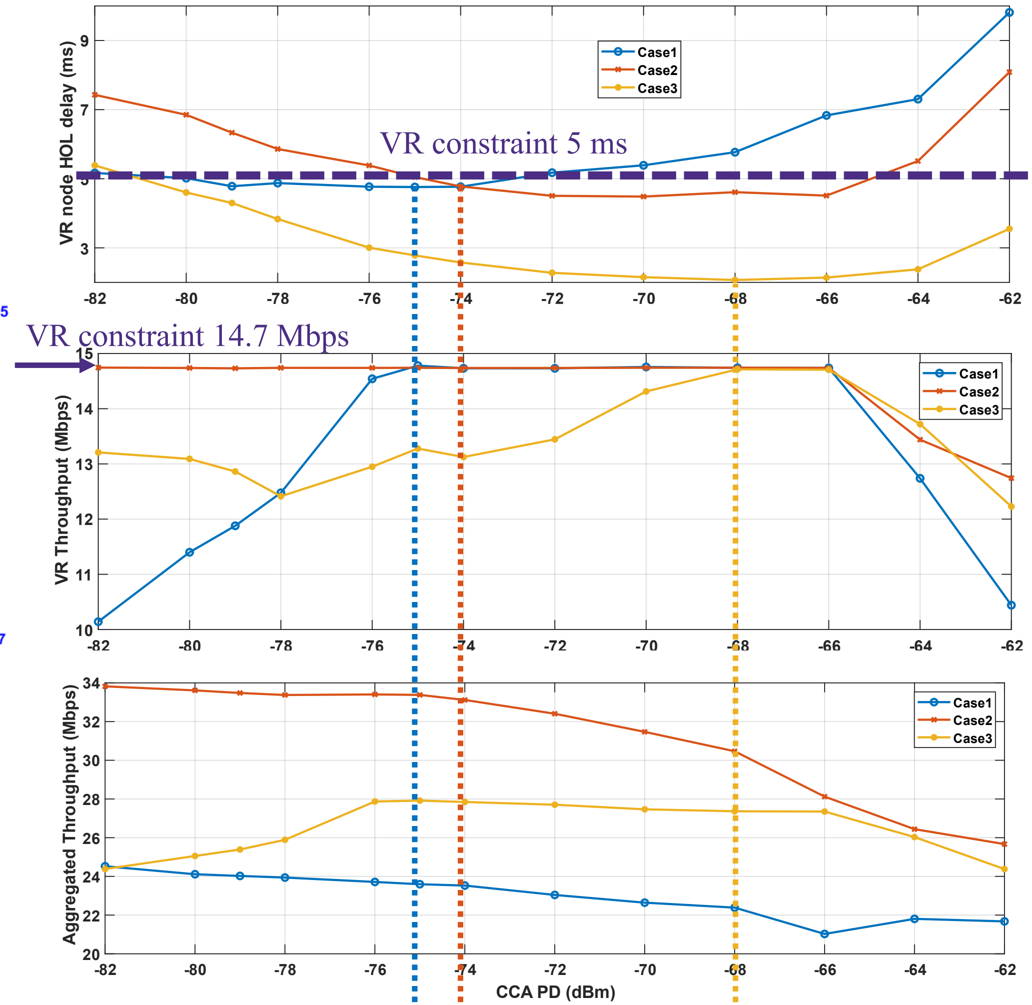
25 m x 25 m



Realization 3

25 m x 25 m





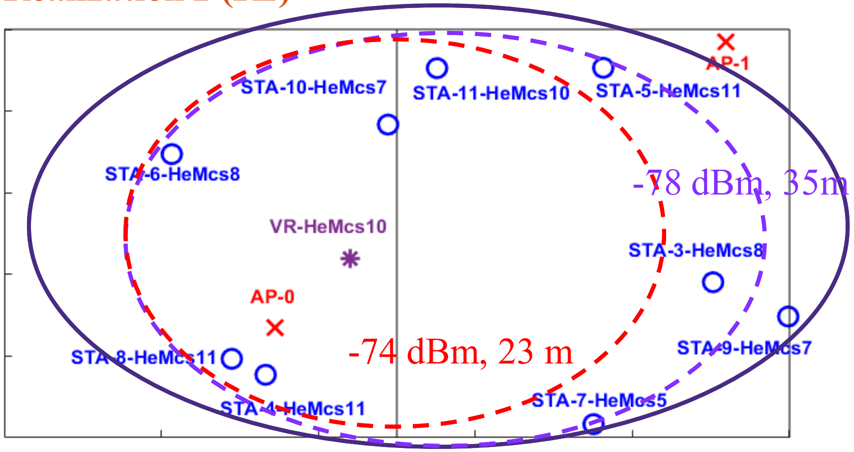
R1: -75 dBm R2: -74 dBm R3: -68 dBm

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

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

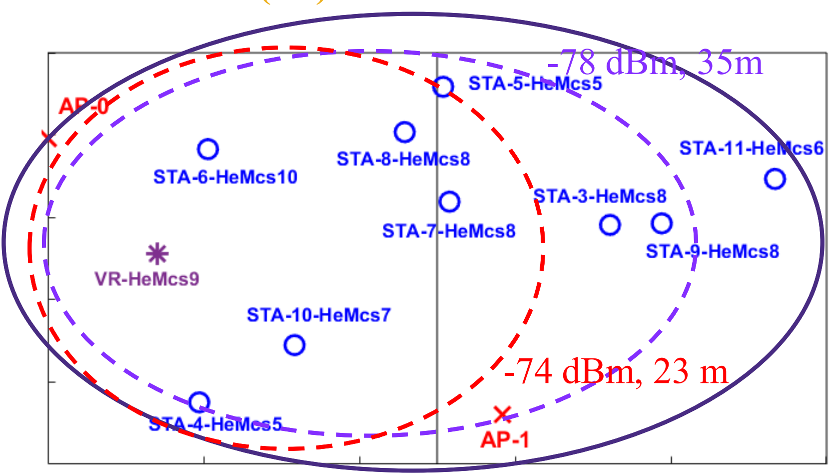
VR/AR TGax Scenario Simulation Examples

Realization 2 (R2)



-82 dBm, 45m

Realization 3 (R3)



-82 dBm, 45m

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

Results	Realization	-82	-78	-74	-72	-70	-68	-64
VR HOL Delay (ms)	R2	7.43	5.86	4.78	4.51	4.48	4.51	7.30
	R3	5.39	3.83	2.58	2.28	2.15	2.07	2.38
VR T'put (Mbps)	R2	14.74	14.74	14.74	14.74	14.74	14.74	12.78
	R3	13.21	12.41	13.12	13.45	14.31	14.71	13.72
Agg-T'put (Mbps)	R2	33.82	33.37	33.12	32.41	31.47	28.12	26.44
	R3	24.38	25.89	27.85	27.70	27.47	27.37	26.03
Num. of nodes heard by VR node	R2	10	9	8	7	6	5	5
	R3	10	8	7	6	6	6	5

R2 MCSs, VR-MCS10:
BSS1: 11, 11, 10, 8, 7
BSS2: 11, 10, 8, 7, 5

R3 MCSs, VR-MCS9:
BSS1: 10, 9, 8, 7, 5
BSS2: 8, 8, 8, 6, 5

For R2:

- VR node and others all have a higher MCS
  - R2 has a larger Aggregated throughput
  - VR nodes fulfilled the t'put target with lower CCA
- R2 has a larger HOL delay since in general VR node can hear more nodes in R2 than the VR node in R3 for the same CCA

For R3:

- VR node and others all have a lower MCS
  - R3 has a smaller aggregated throughput
  - VR nodes fulfilled the t'put target with larger CCA
- R3 has a smaller HOL delay since in general VR node can hear less nodes in R3

Challenges and Motivation

Lessons learned from previous study

> Different Nodes locations per realizations can impact the optimal CCA PD selection
- Various levels of inter-BSS interferences
- Balance the 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 of the real scenarios:

> Transmission power may be different for APs and STAs

> Input may be imperfect: 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!

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

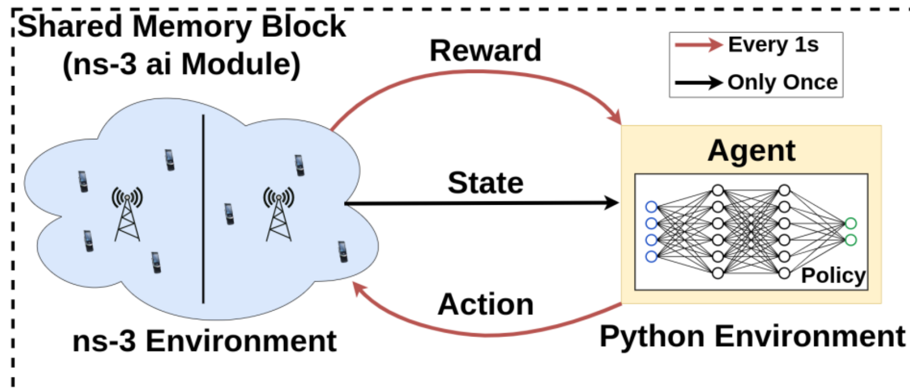
Example: Optimization with DRL and ns3-ai

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)

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

$$N+1$$



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 starts
- 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

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

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

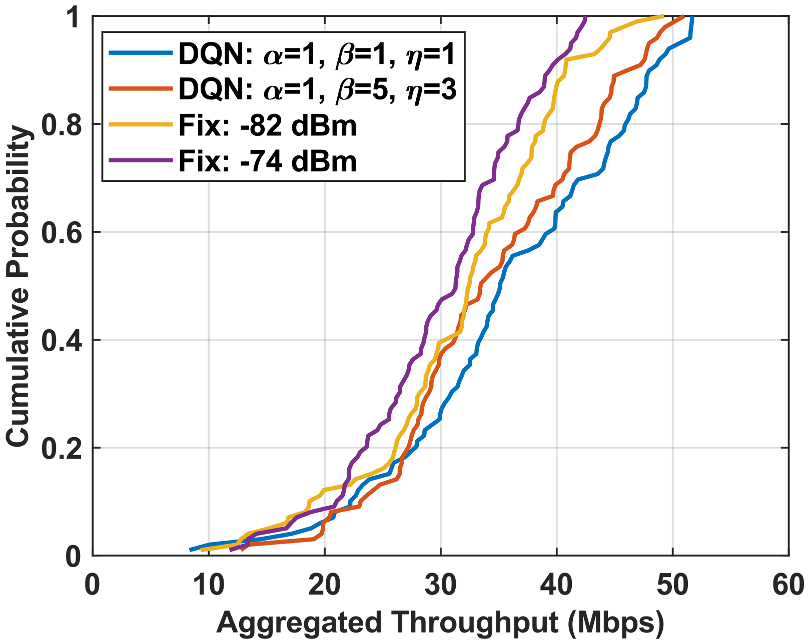
Results

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

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

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.

Backup

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
- The goal is to increase the 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

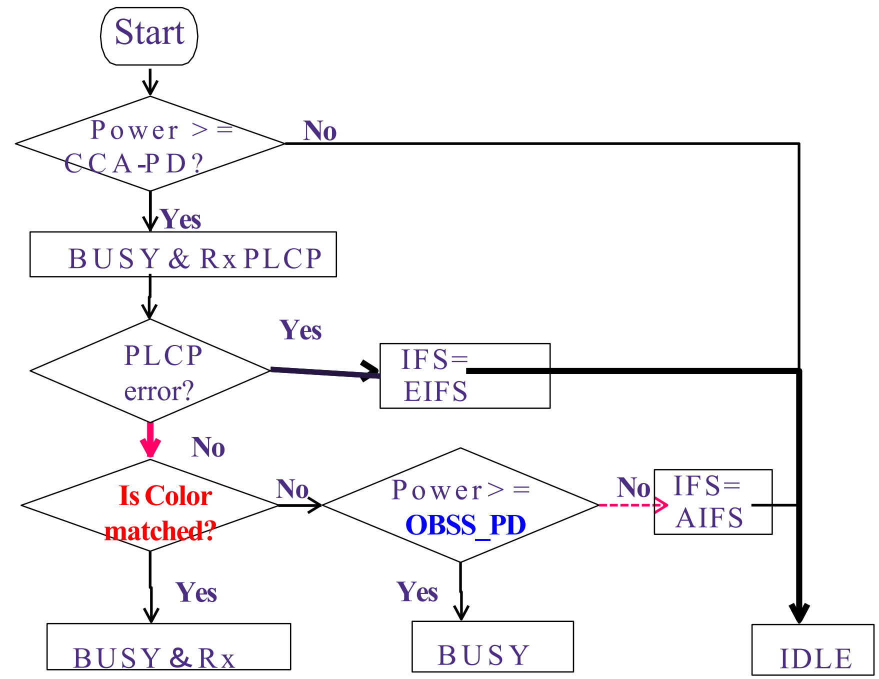


Fig. CCA with BSS Coloring and OBSS_PD

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.

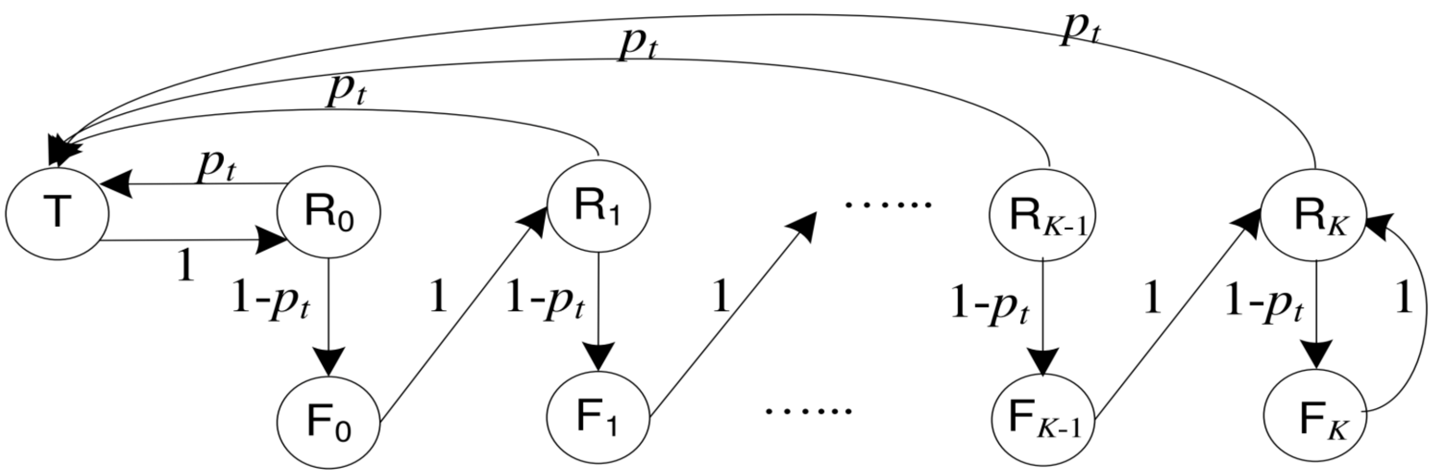
A Unified Analysis of IEEE 802.11 DCF Networks

Stability, Throughput and Delay

[*] L. Dai and X. Sun, "A Unified Analysis of IEEE 802.11 DCF Networks: Stability, Throughput, and Delay," in IEEE Transactions on Mobile Computing, vol. 12, no. 8, pp. 1558-1572, Aug. 2013, doi: 10.1109/TMC.2012.128.

Modeling

> **Embedded Markov chain of HOL packets**
- State R_i: waiting to request, i = 0, . . . , K
- State F_i: collision, i = 0, . . . , K
- State T: successful transmission



Modeling

> Dynamic trajectory of p_t

- For each HOL packet, its transmission is successful if and only if: (1) all the other n − 1 nodes are either idle with an empty queue, or (2) State-Ri HOL packet but not requesting any transmission.

$$p_{t+1} = \left\{ \frac{1 - \rho_t + \rho_t \cdot \sum_{i=0}^{K} \tilde{\pi}_{R_i,t} \cdot (1 - q_i)}{1 - \rho_t + \rho_t \cdot \sum_{i=0}^{K} \tilde{\pi}_{R_i,t}} \right\}^{n-1}.$$

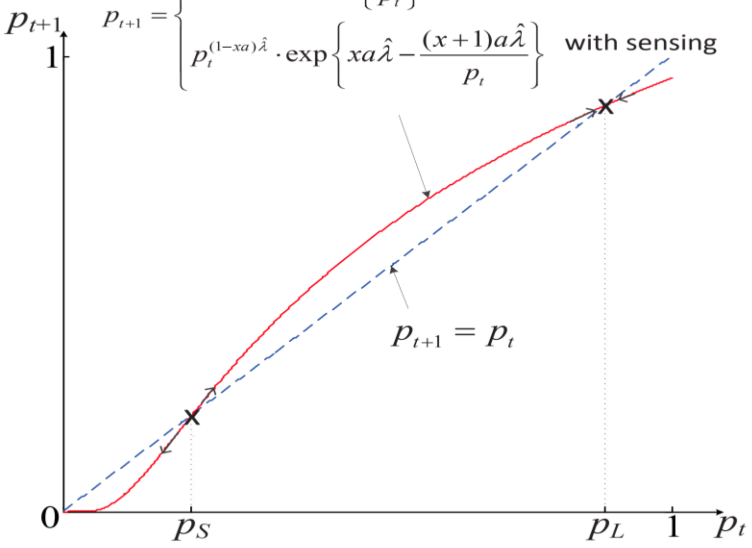
- q_i: Transmission probability of a State-R_i HOL packet
- ρ_t: Offered load at time slot t
- $\pi^{\sim}_{Ri,t}$: Probability that the HOL packet stays at State R_i at time slot t

Modeling

> **Bi-stable Property of p_t**

- $\hat{\lambda}$: aggregate input rate of nodes
- a: time-slot length
- x: collision-detection time in the unit of time slots

$$p_{t+1} = \begin{cases} \exp\left\{\frac{\hat{\lambda}}{p_t}\right\} & \text{without sensing} \\ p_t^{(1-xa)\hat{\lambda}} \cdot \exp\left\{xa\hat{\lambda} - \frac{(x+1)a\hat{\lambda}}{p_t}\right\} & \text{with sensing} \end{cases}$$



Modeling

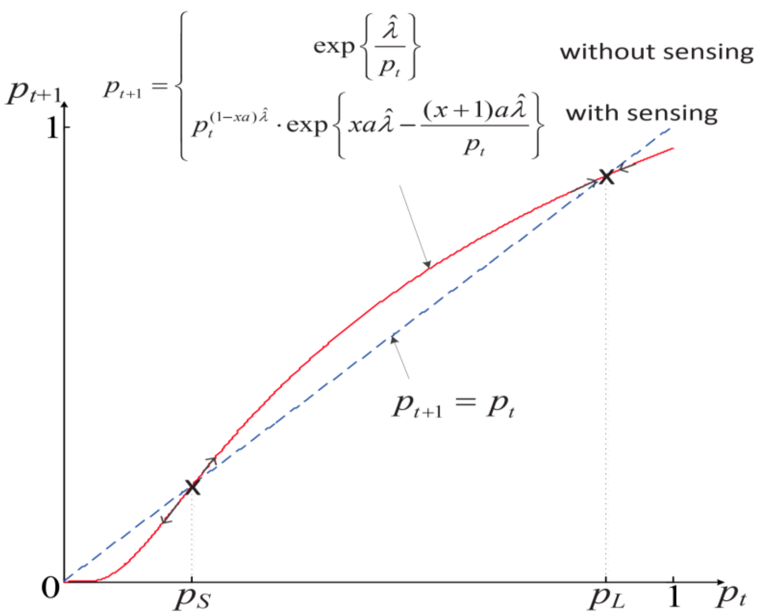
> **Desired Stable Point p_L and Undesired Stable Point p_A**

- If pt ≥ pS at any t and $\lim_{t\to\infty} \rho_t = \rho \leq 1$:

  $\lim_{t\to\infty} p_t \to p_L$

- Otherwise:

  $\lim_{t\to\infty} p_t \to p_A$



Modeling

> **Desired Stable Point p_L and Undesired Stable Point p_A**

- Desired Stable Point pL is determined by the aggregate input rate λˆ and independent of the backoff parameters {qi}
- Undesired Stable Point pA is determined by the backoff parameters {qi} and the number of nodes n

	Without Sensing	With Sensing
Desired Stable Point p_L	$p_L^{Aloha} = \exp\left\{\mathbb{W}_0(-\hat{\lambda})\right\}$	$p_L^{CSMA} = \exp\left\{\mathbb{W}_0\left(-\frac{(x+1)a\hat{\lambda}}{1-(1-xa)\hat{\lambda}}\cdot\exp\left\{-\frac{xa\hat{\lambda}}{1-(1-xa)\hat{\lambda}}\right\}\right)+\frac{xa\hat{\lambda}}{1-(1-xa)\hat{\lambda}}\right\}$
Undesired Stable Point p_A	$p_A = \exp\left\{-\frac{n}{\sum_{i=0}^{K-1}\frac{p_A(1-p_A)^i}{q_i}+\frac{(1-p_A)^K}{q_K}}\right\}$	

Modeling

> **Service Rate and Service Time Distribution**

- Service rate

$$\frac{-p \ln p}{(x+1)a-(1-xa)p \ln p-xap}$$

- Service time distribution

$$\begin{cases} G_{D_i}(z) = pz^{\tau_T} G_{Y_i}(z) + (1-p)z^{\tau_F} G_{Y_i}(z) G_{D_{i+1}}(z), i<K \\ G_{D_K}(z) = pz^{\tau_T} G_{Y_K}(z) + (1-p)z^{\tau_F} G_{Y_K}(z) G_{D_K}(z), \end{cases}$$

- GX(z) denotes the probability generating function of X.
- D_i denotes the time spent from the beginning of State R_i until the service completion
- Y_i denotes the holding time of a HOL packet in State R_i, i = 0, . . . , K

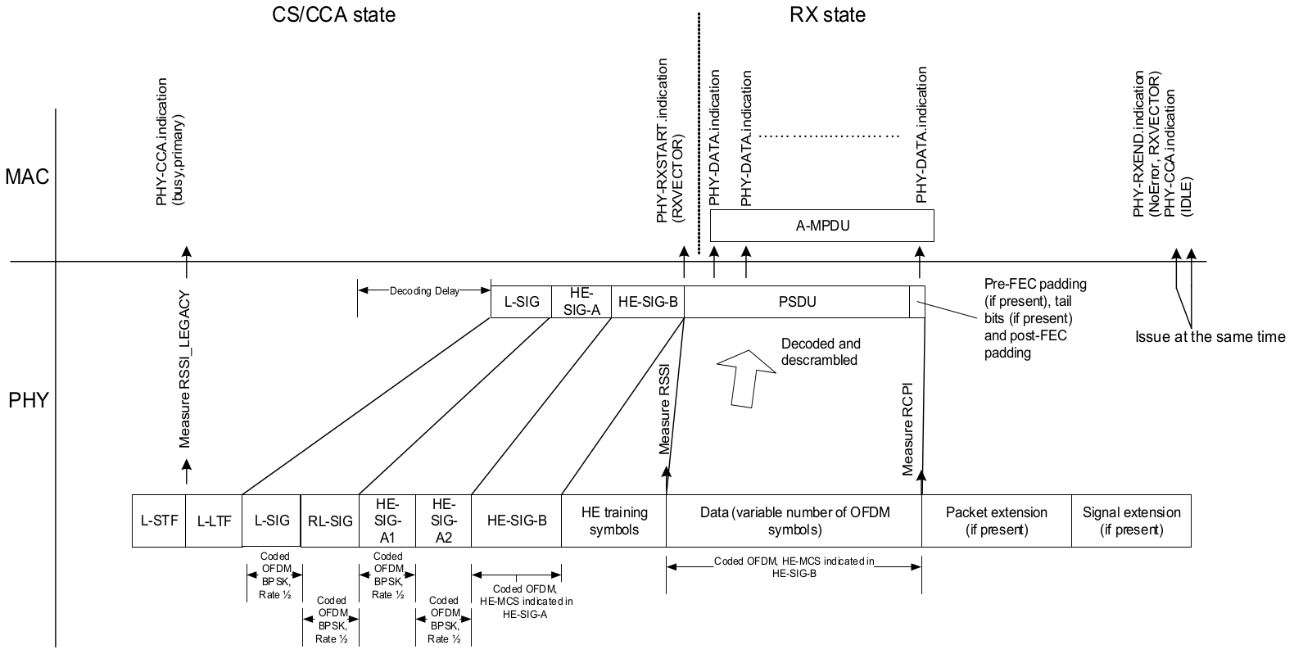
Modeling

> ## Summary

- The key to node-centric modeling lies in proper characterization of 1) the state transition process of each HOL packet, and 2) the steady-state probability of successful transmission of HOL packets.
- Based on the proposed unified analytical framework, effects of key parameters on a wide range of performance metrics such as network throughput, access delay, sum rate and stability, of various random-access networks can be evaluated in a systematic manner.
- The proposed analytical framework can further facilitate performance optimization to reveal the fundamental limits of random-access networks, and to show how to properly set the key system parameters to achieve the limiting performance.

Reception Failure Cases and their ns-3 implementation

PHY receive procedure for an HE SU PPDU



- In ns-3 there are specific labels depending on which field failed reception.
- The frame format of the previous figures (Rx Failure cases) can be extended to the format of an HE SU PPDU to match the labels ns-3 outputs.

[1] "IEEE Standard for Information Technology--Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks--Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 1: Enhancements for High-Efficiency WLAN," in *IEEE Std 802.11ax-2021 (Amendment to IEEE Std 802.11-2020)* , vol., no., pp.1-767, 19 May 2021, doi: 10.1109/IEEESTD.2021.9442429.

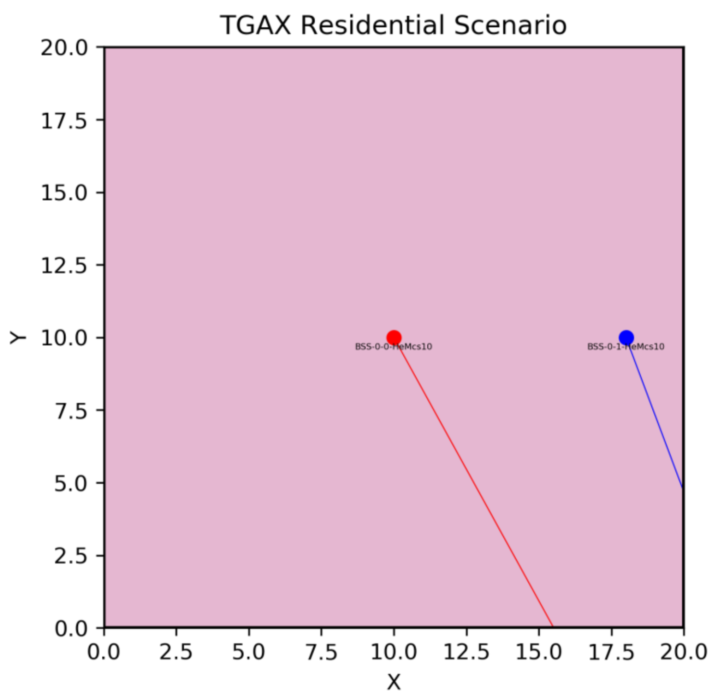
ns-3 Wi-Fi PHY Reception Failure Reasons

```
/**
 * \ingroup wifi
 * Enumeration of the possible reception failure reasons.
 */
enum WifiPhyRxfailureReason
{
    UNKNOWN = 0,
    UNSUPPORTED_SETTINGS,
    CHANNEL_SWITCHING,
    RXING,
    TXING,
    SLEEPING,
    POWERED_OFF,
    TRUNCATED_TX,
    BUSY_DECODING_PREAMBLE,
    PREAMBLE_DETECT_FAILURE,
    RECEPTION_ABORTED_BY_TX,
    L_SIG_FAILURE,
    HT_SIG_FAILURE,
    SIG_A_FAILURE,
    SIG_B_FAILURE,
    U_SIG_FAILURE,
    EHT_SIG_FAILURE,
    PREAMBLE_DETECTION_PACKET_SWITCH,
    FRAME_CAPTURE_PACKET_SWITCH,
    OBSS_PD_CCA_RESET,
    HE_TB_PPDU_TOO_LATE,
    FILTERED,
    DMG_HEADER_FAILURE,
    DMG_ALLOCATION_ENDED
};
```

- This is the list of labels for all possible PHY reception failures in ns-3.
- Their meaning and which of the previously mentioned cases they match will be explained in the following slides.

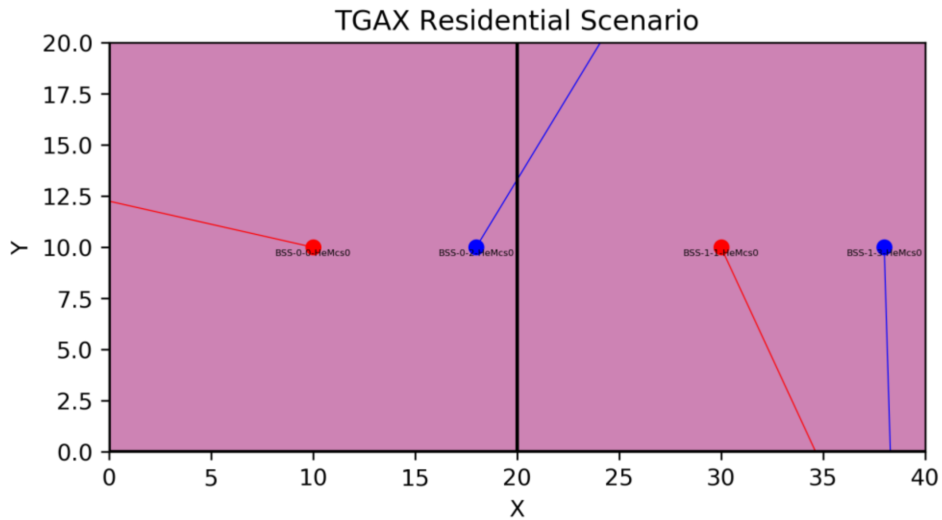
1. Single Node Tx

> One node transmission: No collisions. It is possible to drop a signal for poor channel quality, i.e. far away from the AP and transmitting with low power. Specifically, If (RSSI < CcaSensitivity OR SNR < Threshold(4dB)). NS3 LABEL: PREAMBLE_DETECTION_FAILURE

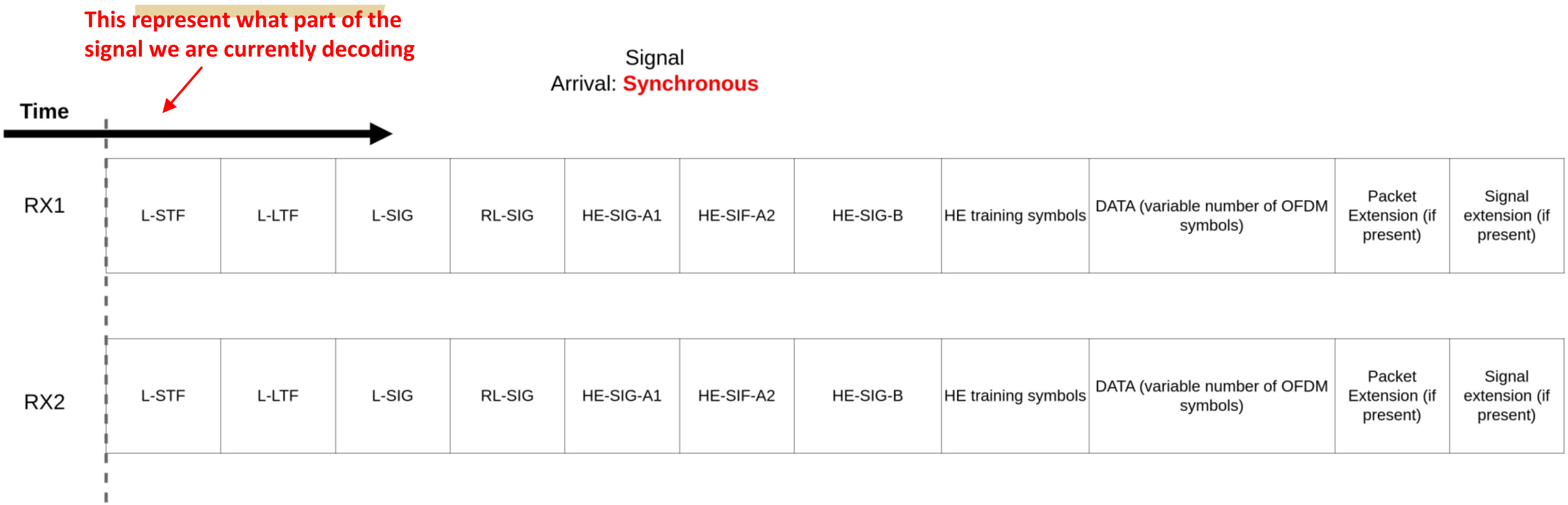


2. Multiple STAs/BSSs: Perfect Sensing Range

- Case 1: Collision due to same backoff window. NS3 outputs 2 possible LABELS: PREAMBLE_DETECTION_FAILURE, BUSY_DECODING_PREAMBLE
- In the next slide the ns-3 logic behind the two labels and what conditions need to be true for them to be triggered are detailed.



Case 1: ns-3 Label and Logic

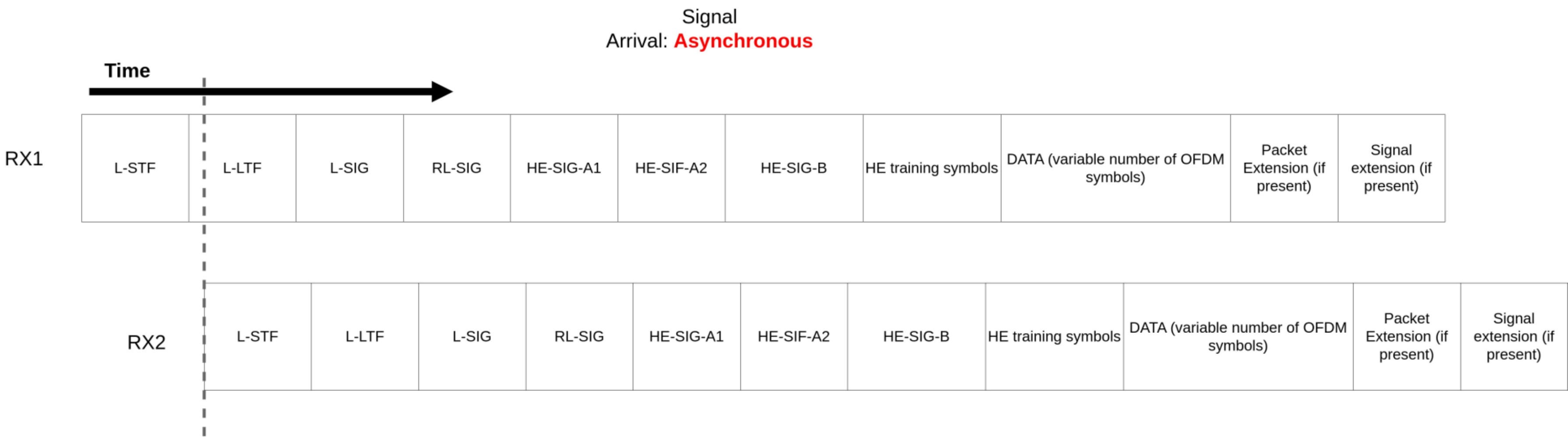


Assume RSSI(**RX1**) is greater than RSSI(**RX2**):

- If (RSSI(**RX1**) > RSSI(**RX2**)) ---> **RX2** PHYDROP = BUSY_DECODING_PREAMBLE (4 us after signal arrival)

- If (RSSI(**RX1**) < CcaSensitivity OR SNR(**RX1**) < Threshold(4dB)) ---> **RX1** PHYDROP = PREAMBLE_DETECT_FAILURE (4 us after signal arrival)

Case 1: ns-3 Label and Logic



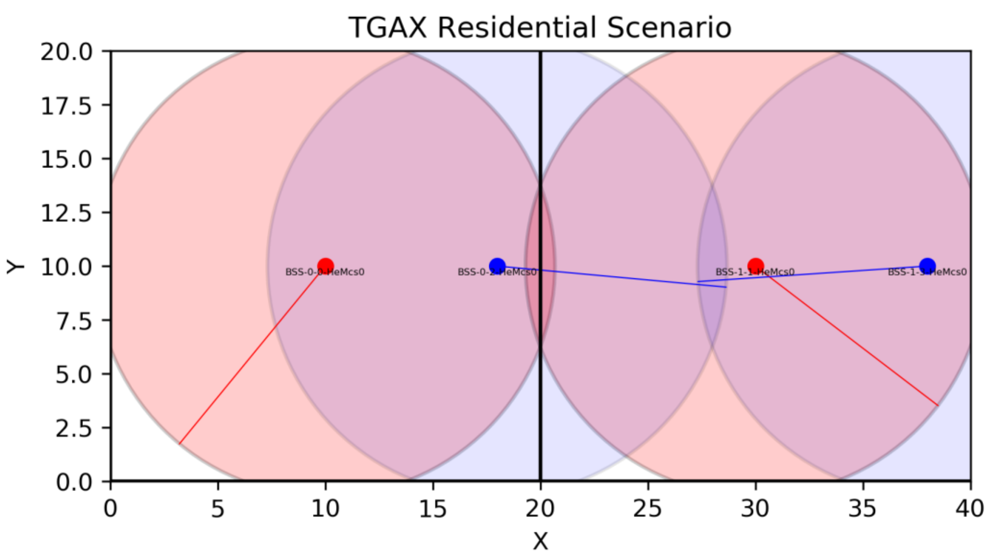
Assume (RSSI(**RX1**) > CcaSensitivity AND SNR(**RX1**) > Threshold(4dB)):

- **RX2** PHYDROP = BUSY_DECODING_PREAMBLE (this happens just as the signal arrives because the receiver is already in CCA_BUSY)

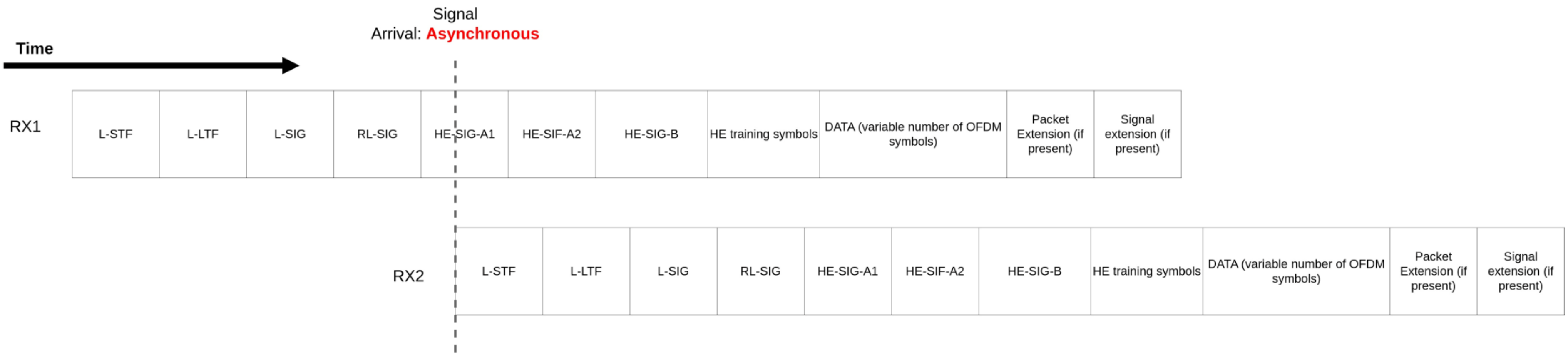
Explanation: WifiPhyState = CCA_BUSY (already locked on to another preamble). The only other option is if frame capture is enabled (which is not) and then it is possible to switch to RX2 producing a FRAME_CAPTURE_PACKET_SWITCH for RX1

3. Multiple STAs/BSSs: Imperfect Sensing Range

- Case 1: Collision due to same backoff window.
- Case 2: Collisions while decoding the PHY header. ns-3 outputs different labels according to which field of the PHY header fails
- Case 3: Collisions while decoding the Payload.



Case 2: Collision on the HE header



Assume (RSSI(**RX1**) > CcaSensitivity AND SNR(**RX1**) > Threshold(4dB)):

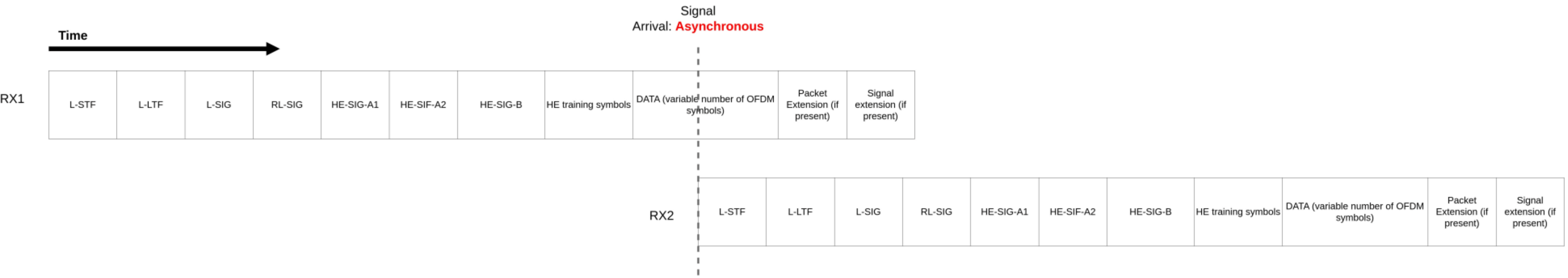
- **RX2** PHYDROP = BUSY_DECODING_PREAMBLE

If(PHY_HEADER_FIELD_PER(**RX1**) < RandomValue()):

- **RX1** PHYDROP = SIG_A_FAILURE

Explanation: The PER of the specific PHY header field is lower than a randomly generated value. The same thing could happen in the HE-SIG-B and the PHY drops will be SIG_B_FAILURE.

Case 3: Collision on the Payload

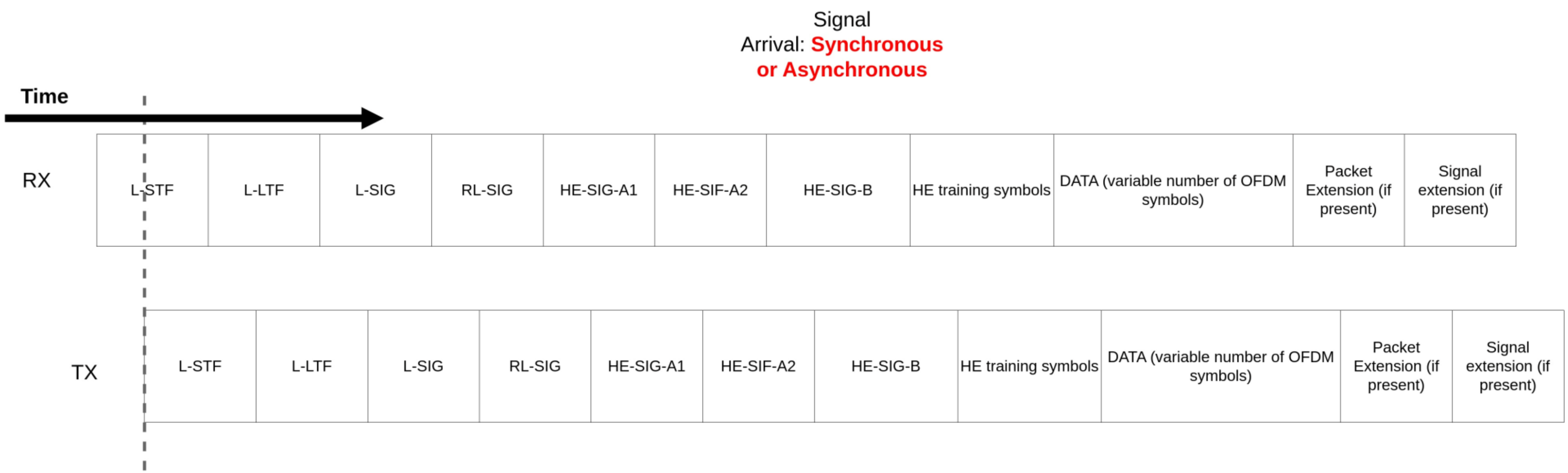


Assume (RSSI(**RX1**) > CcaSensitivity AND SNR(**RX1**) > Threshold(4dB)):

- **RX2** PHYDROP = RXING

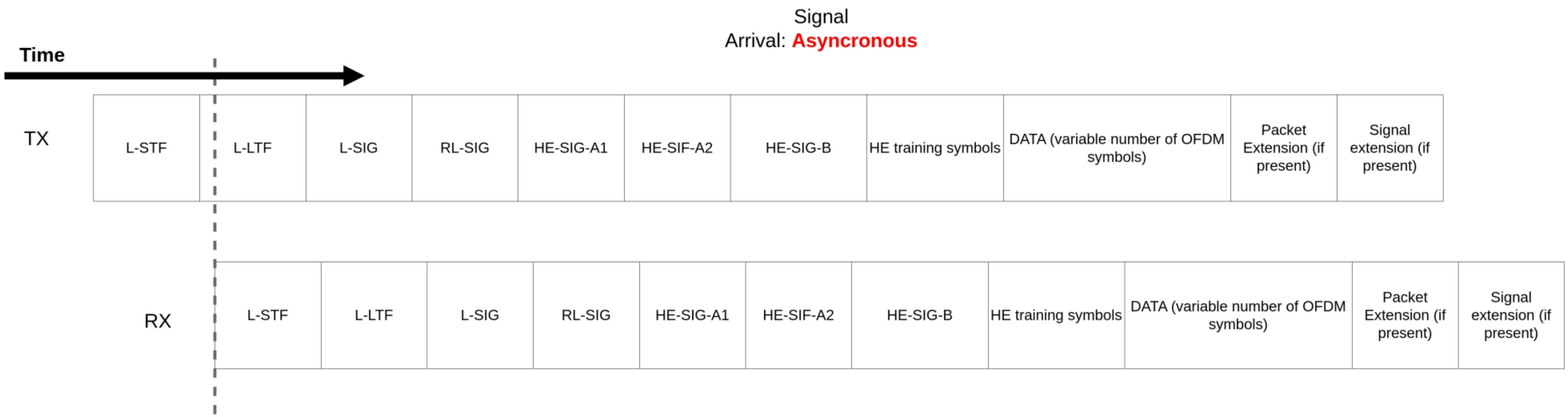
Explanation: WifiPhyState = RX and FrameCapture is disabled

Special Case: Signal Arrival and Transmission



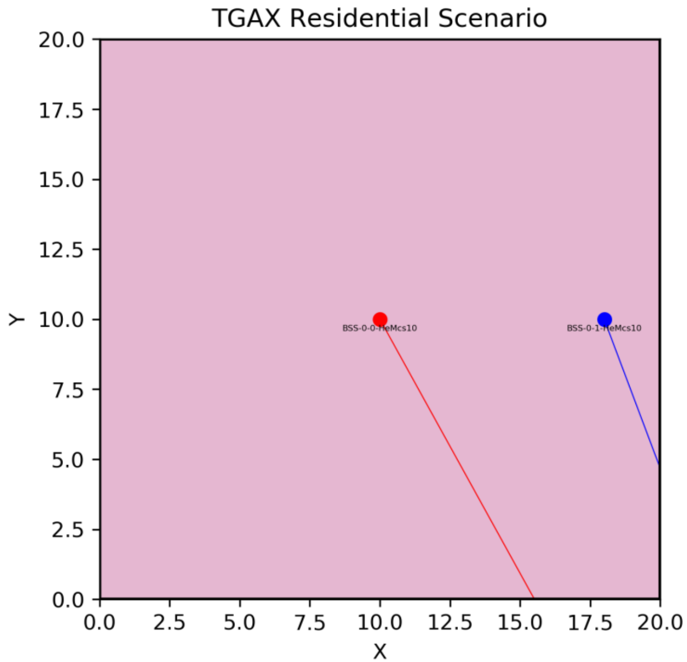
If a signal is to be transmitted during the preamble detection period of **RX** (first 4 us after signal arrival), the received signal **RX** PHYDROP = RECEPTION_ABORTED_BY_TX

Special Case: Transmission and Signal Arrival

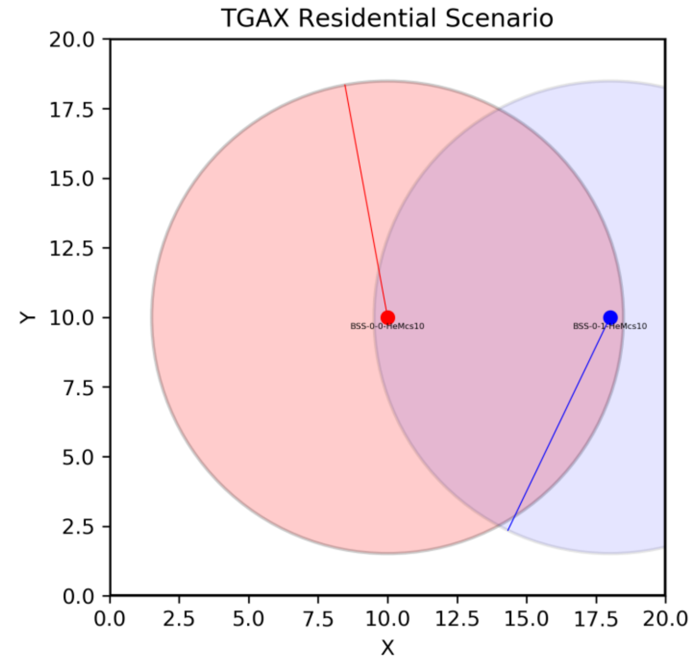


If a signal is being transmitted and a signal is received at any point during the transmission; the received signal **RX** will be dropped due to PHYDROP = TXING

Single Node Tx Statistics



Drop Reason : No Overlapping Tx or Failure



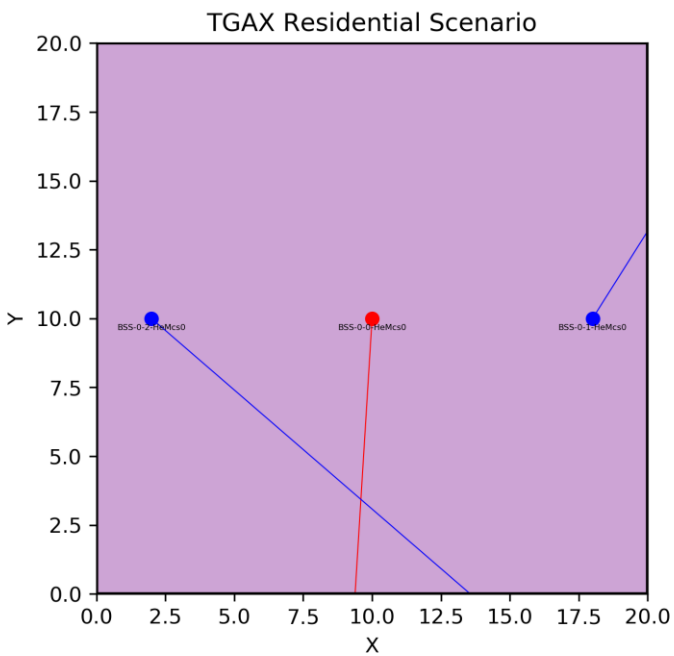
Total Tx Attempts: 28380

Drop Reason :

1. PREAMBLE_DETECT_FAILURE: 7.5%

./ns3 run "tgax-residential --standard=11ax --phyMode=HeMcs0 --pktSize=1500 --duration=5 --gi=800 --channelWidth=20 --rng=1 --apNodes=1 --networkSize=1 --ring=1 --maxMpdus=5 --ccaSensitivity=-52 --txPower=16 --prop=tgax --distance=8 --autoMCS=false --app=constant --pktInterval=5000 --boxsize=20"

Multiple Tx Failure – IntraBSS Statistics



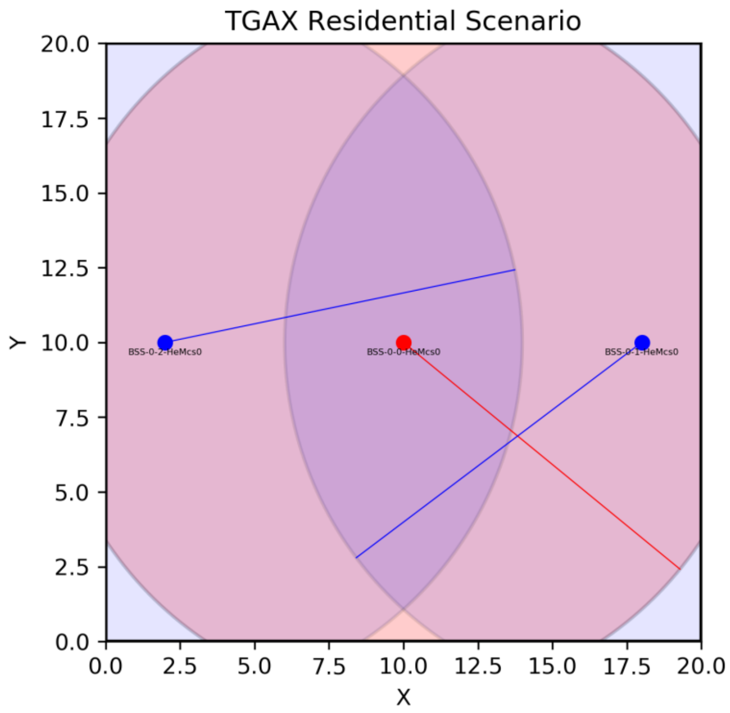
Total Tx Attempts: 7001

Drop Reason :

1. PREAMBLE_DETECT_FAILURE: 3.09%
2. BUSY_DECODING_PREAMBLE: 3.08%
3. TXING: 0.01%

./ns3 run "tgax-residential --standard=11ax --phyMode=HeMcs0 --pktSize=1500 --duration=5 --gi=800 --channelWidth=20 --rng=1 --apNodes=1 --networkSize=2 --ring=1 --maxMpdus=5 --ccaSensitivity=-82 --txPower=16 --prop=tgax --distance=8 --autoMCS=false --app=constant --pktInterval=5000 --boxsize=20"

Multiple Tx Failure – IntraBSS Statistics



Total Tx Attempts: 30998

Drop Reason :

1. PREAMBLE_DETECT_FAILURE: 3.15%
2. RXING : 1.33%
3. BUSY_DECODING_PREAMBLE: 0.1%
4. TXING: 0.04%
5. RECEPTION_ABORTED_BY_TX: 0.01%
6. L_SIG_FAILURE: 0.009%

./ns3 run "tgax-residential --standard=11ax --phyMode=HeMcs0 --pktSize=1500 --duration=5 --gi=800 --channelWidth=20 --rng=1 --apNodes=1 --networkSize=2 --ring=1 --maxMpdus=5 --ccaSensitivity=-52 --txPower=16 --prop=tgax --distance=8 --autoMCS=false --app=constant --pktInterval=5000 --boxsize=20"