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 transmissions!

Throughput – Multi-BSS analysis

2 Overlapping BSS [2]:

- Parameters $d$ (inter-BSS distance), $r$ (BSS transmission range) $\Rightarrow$ 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

\[
\text{SINR} = \frac{P_{rx}}{(P_{int} + \text{Noise})}
\]
\[
P_{rx} = P_{tx} - PL(r)
\]
\[
P_{int} = P_{tx} - PL(r^2 + d^2)
\]

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

---

Throughput – Multi-BSS analysis

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

- Setup: Total 50 STAs (25 STAs in each BSS)
  - $r = 8\text{m}$, $d = 5\text{m}$, $\sqrt{r^2 + d^2} = 9.5\text{m}$, SINR = 2 dB
  - SINR = 2 dB $\rightarrow$ 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 $\sim$ One larger cell

❖ Results:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{rx}$</td>
<td>-61.6 dBm</td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>-64.6 dBm</td>
</tr>
<tr>
<td>Noise</td>
<td>-128 dBm</td>
</tr>
<tr>
<td>SINR</td>
<td>2 dB</td>
</tr>
</tbody>
</table>

- Results validated against Bianchi model predictions

Example Codes: [https://gitlab.com/haoyinyh/ns-3-dev/-/tree/multibss](https://gitlab.com/haoyinyh/ns-3-dev/-/tree/multibss)
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:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{rx}$</td>
<td>-65 dBm</td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>-77.2 dBm</td>
</tr>
<tr>
<td>Noise</td>
<td>-128 dBm</td>
</tr>
<tr>
<td>SINR</td>
<td>12 dB</td>
</tr>
</tbody>
</table>

- 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)
  - $r = 3\text{m}, d = 20\text{m}, \sqrt{r^2 + d^2} = 20.3\text{m}, \text{SINR} = 28.9\text{ dB}$
  - SINR = 28.9 dB → Can support successful simultaneous 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:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{rx}$</td>
<td>-46.7 dBm</td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>-75 dBm</td>
</tr>
<tr>
<td>Noise</td>
<td>-128 dBm</td>
</tr>
<tr>
<td>SINR</td>
<td>28.9 dB</td>
</tr>
</tbody>
</table>

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)

- 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)
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 $\lambda$, i.e., each STA has probability $\lambda$ to generate a new packet every $\tau_T$ time [3].
- $\tau_T$ time is the channel holding time at MAC layer for each frame

\[
\text{Bernoulli} \left( \frac{\lambda}{\tau_T} \right): \quad \xrightarrow{\tau_T} \xrightarrow{\tau_T} \xrightarrow{\tau_T} \xrightarrow{\tau_T}
\]

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

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]

<table>
<thead>
<tr>
<th>Cases</th>
<th>Scale by number of STAs</th>
<th>Scale by initial CW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Saturated:</strong></td>
<td>n=[5,...,50] (^1)</td>
<td></td>
</tr>
<tr>
<td>(\lambda = 1), time=30s</td>
<td>w=15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>k=6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>n=15</td>
<td>w=[15,...,1023] (^2)</td>
</tr>
<tr>
<td></td>
<td>k=6</td>
<td></td>
</tr>
<tr>
<td><strong>Unsaturated:</strong></td>
<td>n=[5,...,50] (^1)</td>
<td></td>
</tr>
<tr>
<td>(\lambda = 0.15), time=200s</td>
<td>w=15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>k=6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>n=15</td>
<td>w=[15,...,1023] (^2)</td>
</tr>
<tr>
<td></td>
<td>k=6</td>
<td></td>
</tr>
</tbody>
</table>

\(\lambda\) = 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 \(2^{10}\)

Delay Validation - Analytical Model

Access Delay:

- **Saturated** Case
  - Mean delay

\[
E[D_0] = G'_D_0(1) = \frac{1-p}{p} \tau_F \cdot \frac{1}{\alpha} \cdot \left( \frac{1}{2p} + \frac{W}{2} \left( \frac{1}{1-\frac{1-p}{q}} + \left( \frac{1}{p} - 1 + \frac{1-p}{q} \right) \cdot \left( \frac{1-p}{q} \right)^K \right) \right)
\]

- **Unsaturated** Case: e.g., with fixed \( \hat{\lambda} = n \lambda = 0.15 \), the aggregate input data rate for \( n \) nodes

\[
E[D_{0,p=p_L}] \approx \tau_T + \frac{1+W}{2}
\]

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

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


More details - see backup slides
Delay Analysis

- 802.11ax, CwMin=16, CwMax = $2^6\times$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 $\rightarrow$ more nodes, more collisions
  - Under **Unsaturated** condition: delay is constant $\rightarrow$ with fixed aggregate rate, low collisions

- 802.11ax, nSTA = 15, CwMax = $2^6\times$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 $\rightarrow$ the tradeoff between less collisions and long backoff period
  - Under **Unsaturated** condition, delay increases with CwMin $\rightarrow$ 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

At STA1

\[ P_{rx1}(STA2) = P_{tx}(STA2) - PL(r+d+r) = -82 \text{ dBm} \]
\[ P_{rx1}(AP2) = P_{tx}(AP2) - PL(r+d) = -79 \text{ dBm} \]

At AP1

\[ P_{rx1}(STA2) = P_{tx}(STA2) - PL(r+d) = -79 \text{ dBm} \]
\[ P_{rx1}(AP2) = P_{tx}(AP2) - PL(d) = -76 \text{ dBm} \]

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

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

Log distance propagation model

\[ PL(dis) = L_0 + 10 \times n \times \log_{10} \left( \frac{dis}{d_0} \right) \]

\( n \): the path loss distance exponent, \( n=3.5 \)
\( d_0 \): reference distance, \( d_0 = 1 \text{ m} \)
\( L_0 \): path loss at reference distance (dB), \( L_0 = 50 \)

r = 5 m, d=20 m, \( P_{tx} = 20 \text{ dBm} \)
Changing CCA: Simple 2-BSS case

**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**

<table>
<thead>
<tr>
<th>MCS</th>
<th>$P_e(24,\text{dB})$</th>
<th>$P_e(21,\text{dB})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0.27</td>
</tr>
<tr>
<td>6</td>
<td>0.001</td>
<td>0.99</td>
</tr>
<tr>
<td>7</td>
<td>0.05</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Sinr(AP1) =**

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

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

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

- 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

Packet error rate for different MCSs and SINR

<table>
<thead>
<tr>
<th>MCS</th>
<th>Single BSS</th>
<th>CCA &lt;= -82</th>
<th>CCA &gt; -76</th>
<th>2*Single BSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0.27</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.001</td>
<td>0.99</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.05</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

\[ P_{rx1(STA2)} = -82 \text{ dBm} \]
\[ P_{rx1(AP2)} = -79 \text{ dBm} \]

\[ P_{rx1(STA2)} = -79 \text{ dBm} \]
\[ P_{rx1(AP2)} = -76 \text{ dBm} \]
Simulation Results

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

\[ P_{rx1}(STA2) = -82 \text{ dBm} \]
\[ P_{rx1}(AP2) = -79 \text{ dBm} \]

- 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!

Packet error rate for different MCSs and SINR

<table>
<thead>
<tr>
<th>MCS</th>
<th>Single BSS</th>
<th>CCA &lt;= -82</th>
<th>CCA &gt; -76</th>
<th>2*Single BSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>46.3</td>
<td>50.4</td>
<td>91.9</td>
<td>92.6</td>
</tr>
<tr>
<td>7</td>
<td>51.4</td>
<td>61.2</td>
<td>88.9</td>
<td>102.8</td>
</tr>
<tr>
<td>8</td>
<td>56.1</td>
<td>63.0</td>
<td>50.7</td>
<td>112.2</td>
</tr>
</tbody>
</table>
More complex cases: $n_{STA} > 2$

More stations ($n_{STA} = 10$), distributed on a circle, $r = 5m$, $d = 20m$, $P_{tx} = 20$ dBm:

$\rightarrow$ 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.

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
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

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

*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:

\[
PL(d) = 40.05 + 20 \cdot \log_{10} \left( \frac{f_c}{2.4} \right) + 20 \log_{10} \left( \min(d, 5) \right) + 18.3 \cdot (d) \left( \frac{|d+2|}{|d+1| - 0.46} \right) + 5 \text{ (walls)}
\]

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

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

<table>
<thead>
<tr>
<th>Distance to AP</th>
<th>MCS</th>
<th>Distance to AP</th>
<th>MCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 11 m</td>
<td>11</td>
<td>27 m</td>
<td>6</td>
</tr>
<tr>
<td>12 m</td>
<td>10</td>
<td>29 m</td>
<td>5</td>
</tr>
<tr>
<td>13 m</td>
<td>9</td>
<td>31 m</td>
<td>4</td>
</tr>
<tr>
<td>18 m</td>
<td>8</td>
<td>42 m</td>
<td>3</td>
</tr>
<tr>
<td>26 m</td>
<td>7</td>
<td>52 m</td>
<td>2</td>
</tr>
</tbody>
</table>

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 $\leq 5$ ms

**Can we adjust CCA PD in BSS1 to**
- Fulfill the latency constraint & data rate for VR
- Maximize aggregate throughput of network

**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: 14.7 Mbps, 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

- **Realization 1:** 25 m x 25 m
- **Realization 2:** 25 m x 25 m
- **Realization 3:** 25 m x 25 m

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

**VR constraint 14.7 Mbps**

**VR constraint 5 ms**

**R1:** -75 dBm  
**R2:** -74 dBm  
**R3:** -68 dBm
VR/AR TGax Scenario Simulation Examples

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

<table>
<thead>
<tr>
<th>Results</th>
<th>Realization</th>
<th>-82</th>
<th>-78</th>
<th>-74</th>
<th>-72</th>
<th>-70</th>
<th>-68</th>
<th>-64</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR HOL</td>
<td>R2</td>
<td>7.43</td>
<td>5.86</td>
<td>4.78</td>
<td>4.51</td>
<td>4.48</td>
<td>4.51</td>
<td>7.30</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>5.39</td>
<td>3.83</td>
<td>2.58</td>
<td>2.28</td>
<td>2.15</td>
<td>2.07</td>
<td>2.38</td>
</tr>
<tr>
<td>VR T'put (Mbps)</td>
<td>R2</td>
<td>14.74</td>
<td>14.74</td>
<td>14.74</td>
<td>14.74</td>
<td>14.74</td>
<td>14.74</td>
<td>12.78</td>
</tr>
<tr>
<td>Agg-T'put (Mbps)</td>
<td>R2</td>
<td>33.82</td>
<td>33.37</td>
<td>33.12</td>
<td>32.41</td>
<td>31.47</td>
<td>28.12</td>
<td>26.44</td>
</tr>
<tr>
<td></td>
<td>R3</td>
<td>24.38</td>
<td>25.89</td>
<td>27.85</td>
<td>27.70</td>
<td>27.47</td>
<td>27.37</td>
<td>26.03</td>
</tr>
<tr>
<td>Num. of nodes</td>
<td>R2</td>
<td>10</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>heard by VR</td>
<td>R3</td>
<td>10</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

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)

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

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

**Reward**: Aggregated throughput, VR Throughput and delay
\[
r_t = \alpha * T_{pt} + \beta * (T_{constraint} - H_{ol}) + \eta * (T_{pt_{required}} - T_{pt_{vr}})
\]

* For simplicity, we design this linear combination of throughput and delay. The \( \alpha \), \( \beta \) and \( \eta \) 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:

$$Q(s, a) = \frac{Q(s, a)}{\text{old value}} + \sigma \theta \left[ \frac{r'}{\text{reward}} + \gamma \frac{\gamma}{\text{discount factor}} \frac{\max_{a'} Q(s', a')}{\text{expected optimal value}} - \frac{Q(s, a)}{\text{old value}} \right]$$

We need approximation for the Q function – Deep neural networks

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

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

<table>
<thead>
<tr>
<th>Target</th>
<th>Fix: -82</th>
<th>Fix: -78</th>
<th>Fix: -74</th>
<th>Fix: -70</th>
<th>Fix: -68</th>
<th>DQN: α = 1, β = 1, η = 1</th>
<th>DQN: α = 1, β = 5, η = 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR Delay</td>
<td>74%</td>
<td>76%</td>
<td>85%</td>
<td>81%</td>
<td>75%</td>
<td>88%</td>
<td>94%</td>
</tr>
<tr>
<td>VR Throughput</td>
<td>56%</td>
<td>64%</td>
<td>68%</td>
<td>74%</td>
<td>62%</td>
<td>84%</td>
<td>93%</td>
</tr>
</tbody>
</table>

Fix CCA-PD threshold

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
\[ r_t = \alpha \cdot T_{pt} + \beta \cdot (T_{constraint} - Hol) + \eta \cdot (T_{pt\ required} - T_{pt\ vr}) \]
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

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.

A Unified Analysis of IEEE 802.11 DCF Networks

Stability, Throughput and Delay

Modeling

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

\textbf{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.

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

- \( q_i \): Transmission probability of a State-Ri HOL packet
- \( \rho_t \): Offered load at time slot \( t \)
- \( \pi_{\sim R_i,t} \): Probability that the HOL packet stays at State \( R_i \) at time slot \( t \)
Bi-stable Property of $p_t$

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

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

> Desired Stable Point $p_L$ and Undesired Stable Point $p_A$
  
  • If $p_t \geq p_S$ 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 $p_L$ is determined by the aggregate input rate $\hat{\lambda}$ and independent of the backoff parameters $\{q_i\}$
- Undesired Stable Point $p_A$ is determined by the backoff parameters $\{q_i\}$ and the number of nodes $n$

<table>
<thead>
<tr>
<th></th>
<th>Without Sensing</th>
<th>With Sensing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired Stable Point</td>
<td>$p_{L}^{Aloha} = \exp{\mathbb{W}_0(-\hat{\lambda})}$</td>
<td>$p_{L}^{CSMA} = \exp\left{\mathbb{W}_0\left(-\frac{(x+1)a\hat{\lambda}}{1-(1-xa)\hat{\lambda}}\right) \cdot \exp\left{-\frac{xa\hat{\lambda}}{1-(1-xa)\hat{\lambda}}\right}\right} + \frac{xa\hat{\lambda}}{1-(1-xa)\hat{\lambda}}$</td>
</tr>
<tr>
<td>Undesired Stable</td>
<td>$p_A = \exp\left{-\frac{n}{\sum_{i=0}^{K-1} \frac{p_A(1-p_A)^i}{q_i} + \frac{(1-p_A)^K}{q_K}}\right}$</td>
<td>$p_A$</td>
</tr>
<tr>
<td>Point $p_A$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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

\[
\begin{align*}
G_{D_i}(z) &= p z^{\tau_T} G_{Y_i}(z) + (1-p) z^{\tau_F} G_{Y_i}(z) G_{D_{i+1}}(z), \quad i < K \\
G_{D_K}(z) &= p z^{\tau_T} G_{Y_K}(z) + (1-p) z^{\tau_F} G_{Y_K}(z) G_{D_K}(z),
\end{align*}
\]

- \(GX(z)\) 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 \(R_i\), \(i = 0, \ldots, K\)
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.

ns-3 Wi-Fi PHY Reception Failure Reasons

- 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 $\text{RSSI}(RX1) > \text{RSSI}(RX2)$:

- If $\text{RSSI}(RX1) > \text{RSSI}(RX2)$ \(\rightarrow\) RX2 $\text{PHYDROP} = \text{BUSY\_DECODING\_PREAMBLE}$ (4 us after signal arrival)

- If $\text{RSSI}(RX1) < \text{CcaSensitivity}$ OR $\text{SNR}(RX1) < \text{Threshold}(4\text{dB})$ \(\rightarrow\) RX1 $\text{PHYDROP} = \text{PREAMBLE\_DETECT\_FAILURE}$ (4 us after signal arrival)
Case 1: ns-3 Label and Logic

Assume \(\text{RSSI}(RX1) > \text{CcaSensitivity AND SNR}(RX1) > \text{Threshold}(4\text{dB})\):

- **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.
Assume $\text{RSSI}(\text{RX1}) > \text{CcaSensitivity}$ AND $\text{SNR}(\text{RX1}) > \text{Threshold}(4\text{dB})$:

- **RX2** PHYDROP = BUSY_DECODING_PREAMBLE

If($\text{PHY\_HEADER\_FIELD\_PER(}\text{RX1}) < \text{RandomValue()}$):

- **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 \((\text{RSSI}(\mathbf{RX1}) > \text{CcaSensitivity}) \text{ AND } \text{SNR(\mathbf{RX1})} > \text{Threshold}(4\text{dB})):\n
- \textbf{RX2} PHYDROP = RXING

Explanation: WifiPhyState = RX and FrameCapture is disabled
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
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"