Wi-Fi module: Recent changes and future work

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Outline

- Background on ns-3 Wi-Fi module
- How does it presently work?
- Recent changes to the mainline ns-3-dev Wi-Fi models
- Plans for future evolution of the models

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> Credit is due to ns-3's long list of Wi-Fi module maintainers
  - **Mathieu Lacage, Nicola Balco, Ghada Badawy, Getachew Redietab, Matias Richart, Stefano Avallone** (current)**, Sebastien Deronne** (current)

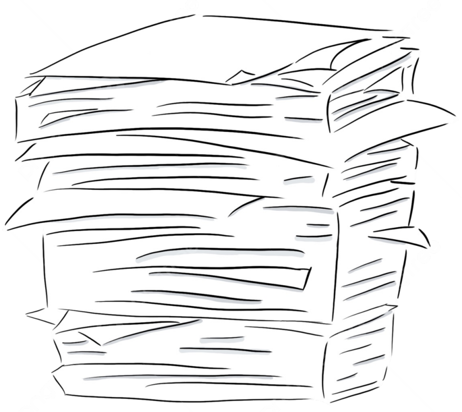
> Portions of the work described have been funded by NSF award CNS-2016379
  - University of Washington: **Sumit Roy, Hao Yin, Juan Leon**

> Thanks to **Sebastien Deronne** and **Stefano Avallone** for providing comments and corrections on earlier drafts

Wi-Fi evolution

	Rates	Freq.	Modulation	Other
802.11	1,2Mbps	2.4 GHz	DSSS	22 MHz overlapping channels
802.11b	1,2,5.5,11 Mbps	2.4 GHz	DSSS/CCK	22 MHz overlapping channels
802.11a	6..54Mbps	5 GHz	OFDM	20 MHz channels
802.11g	1..54Mbps	2.4/5GHz	OFDM in 5 GHz, OFDM/DSSS/CCK in 2.4 GHz	
802.11n	6..600Mbps	2.4/5GHz	OFDM	MIMO, WMM, 20/40 MHz
802.11ac	up to 7Gbps	5 GHz	OFDM	beamforming, DL MU-MIMO 20/40/80/160 MHz
802.11ax	up to 9.6Gbps	2.4/5/6 GHz	OFDM	DL/UL MU-MIMO, spatial reuse, TWT, OFDMA
802.11be	up to 40Gbps	2.4/5/6 GHz	OFDM	320MHz, AP coordination, TSN, MLO, ...
802.11bn	Wi-Fi 8: TBD			

ns-3 Wi-Fi modeling



802.11-2020 standard (through Wi-Fi 6) is 4379 pages, 50 MB !!

- ns-3 only implements portions of the Wi-Fi standards
- Many of the most interesting Wi-Fi aspects are not standardized, and details are proprietary

How can we ever hope to model this?

What is in the ns-3 Wi-Fi models?

Portions of **802.11a**, **802.11b**, **802.11g**, **802.11n** (both 2.4 and 5 GHz bands), **802.11ac**, **802.11ax** (2.4, 5 and 6 GHz bands) and **802.11be** physical layers

> Legacy support (802.11ac and earlier)

- Basic 802.11 **DCF** with infrastructure and adhoc modes
- QoS-based **EDCA** and queueing extensions of 802.11e
- **MSDU aggregation** and **MPDU aggregation** extensions of 802.11n, and both can be combined together (two-level aggregation)
- Various **rate control algorithms** including Aarf, Arf, Cara, Onoe, Rraa, ConstantRate, Minstrel and Minstrel-HT (2012)
- Support for **multiple channel widths** and **spatial streams**
- **AWGN PER curves** for all MCSes
- **802.11s** (mesh module)

802.11ax/be support in ns-3

> **DL OFDMA** (three ack sequences)
> **UL OFDMA** (Basic TF, BSRP TF, Multi-STA Block Ack)
> **MU EDCA** Parameter Set
> Spatial Reuse (**OBSS-PD**) but without rate control awareness
> Per-20 MHz channel sensing and **dynamic bandwidth operation**
> **6 GHz** band operation
> Multi-Link Operation (**MLO**) Discovery and Setup
> MLO multi-radio in **STR mode**
> **ELMSR** (Enhanced Multi-link Single Radio)
> **MU-MIMO at PHY** layer (minimal MAC functionality)
> **EHT PPDU** formats
> **EHT PHY** support (320 MHz channels) and Ideal rate control support

What is missing from the ns-3 Wi-Fi models?

- 802.11n/ac/ax/be beamforming is not supported
- 802.11 PCF/HCF/HCCA are not implemented
- Channel Switch Announcement is not supported
- Authentication and encryption are missing
- Processing delays are not modeled
- Power save operation
- Cases where RTS/CTS and ACK are transmitted using HT/VHT/HE/EHT formats are not supported
- Energy consumption model does not consider MIMO
- 802.11ax preamble puncturing is supported by the PHY but is currently not exploited by the MAC
- Only minimal MU-MIMO is supported (ideal PHY assumed, no MAC layer yet)

(Demo) wifi-simple-infra.cc

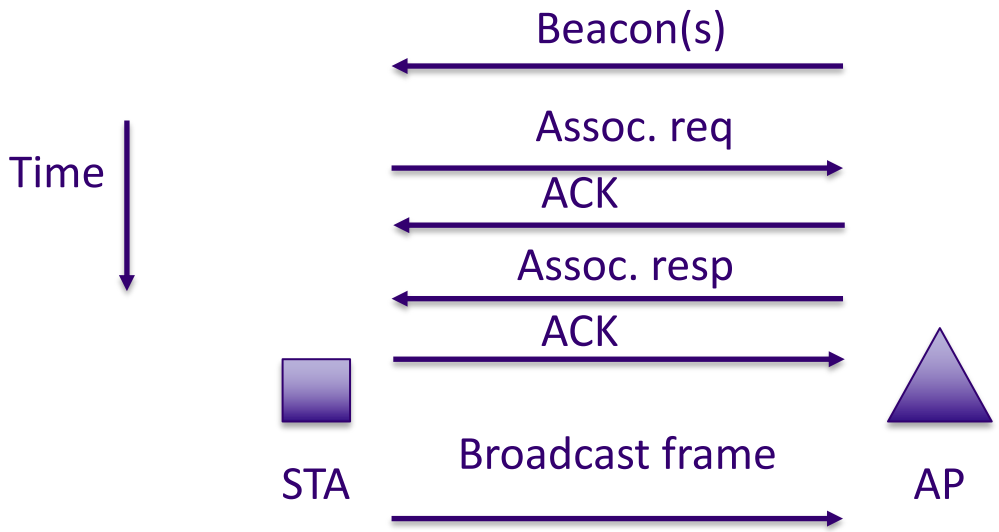
```
./ns3 run wifi-simple-infra
```

> Program output (pcap)

> View Wireshark

> GenerateTraffic()

> `ap-wifi-mac.cc:  packet->AddHeader (beacon);`



Wireshark analysis of this program's PCAP

wifi-simple-infra-0-0.pcap

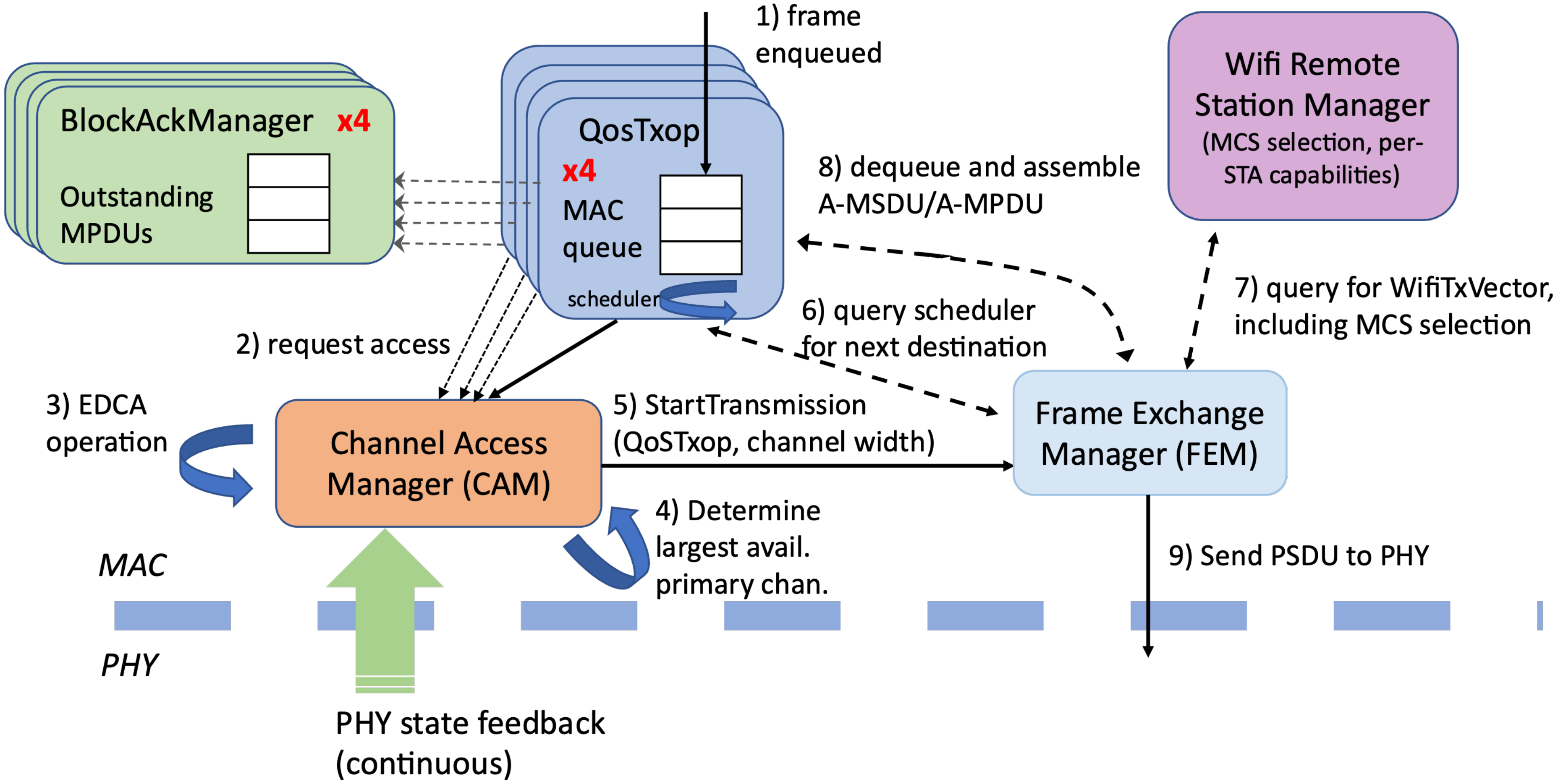
Apply a display filter … <⌘/>

No.	Time	Source	Destination	Protocol	Length	Info
1	0.000000	00:00:00_00:00:02	Broadcast	802.11	87	Beacon frame, SN=0, FN=0, Flags=........C, BI=100, SSID="wifi-default"
2	0.017815	00:00:00_00:00:01	00:00:00_00:00:02	802.11	74	Association Request, SN=0, FN=0, Flags=........C, SSID="wifi-default"
3	0.018737		00:00:00_00:00:01 …	802.11	38	Acknowledgement, Flags=........C
4	0.019299	00:00:00_00:00:02	00:00:00_00:00:01	802.11	64	Association Response, SN=1, FN=0, Flags=........C
5	0.019309		00:00:00_00:00:02 …	802.11	36	Acknowledgement, Flags=........C
6	0.102400	00:00:00_00:00:02	Broadcast	802.11	87	Beacon frame, SN=2, FN=0, Flags=........C, BI=100, SSID="wifi-default"
7	0.204800	00:00:00_00:00:02	Broadcast	802.11	87	Beacon frame, SN=3, FN=0, Flags=........C, BI=100, SSID="wifi-default"
8	0.307200	00:00:00_00:00:02	Broadcast	802.11	87	Beacon frame, SN=4, FN=0, Flags=........C, BI=100, SSID="wifi-default"
9	0.409600	00:00:00_00:00:02	Broadcast	802.11	87	Beacon frame, SN=5, FN=0, Flags=........C, BI=100, SSID="wifi-default"
10	0.512000	00:00:00_00:00:02	Broadcast	802.11	87	Beacon frame, SN=6, FN=0, Flags=........C, BI=100, SSID="wifi-default"
11	0.614400	00:00:00_00:00:02	Broadcast	802.11	87	Beacon frame, SN=7, FN=0, Flags=........C, BI=100, SSID="wifi-default"
12	0.716800	00:00:00_00:00:02	Broadcast	802.11	87	Beacon frame, SN=8, FN=0, Flags=........C, BI=100, SSID="wifi-default"
13	0.819200	00:00:00_00:00:02	Broadcast	802.11	87	Beacon frame, SN=9, FN=0, Flags=........C, BI=100, SSID="wifi-default"
14	0.906519	10.1.1.2	255.255.255.255	UDP	1088	49153 → 80 Len=1000
15	0.921600	00:00:00_00:00:02	Broadcast	802.11	87	Beacon frame, SN=11, FN=0, Flags=........C, BI=100, SSID="wifi-default"

```
> Frame 1: 87 bytes on wire (696 bits), 87 bytes captured (696 bits)
> Radiotap Header v0, Length 24
> 802.11 radio information
> IEEE 802.11 Beacon frame, Flags: ........C
> IEEE 802.11 Wireless Management
```

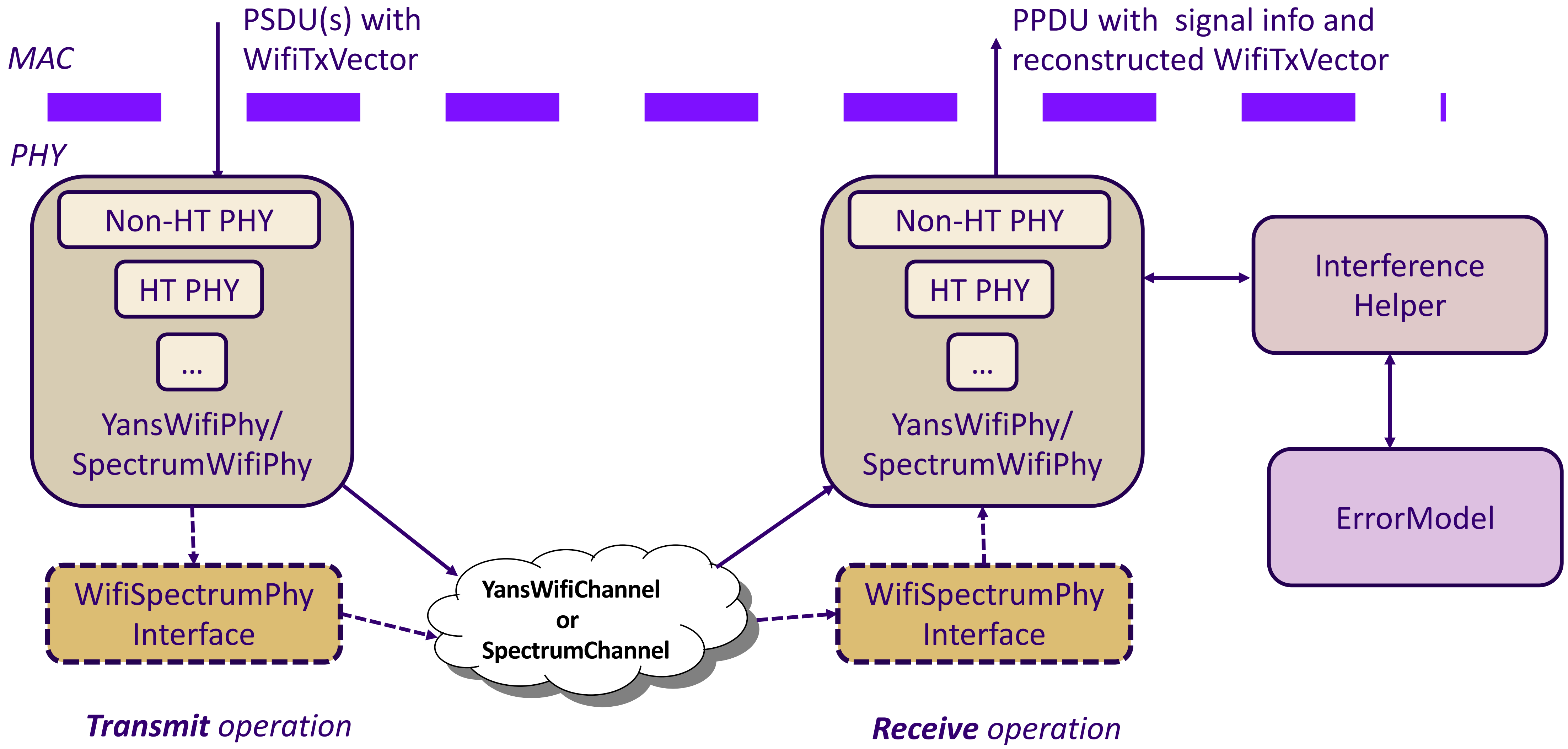
```
0000  00 00 18 00 6f 00 00 00  5b 8f 01 00 00 00 00 00   ····o··· [·······
0010  10 02 6c 09 a0 00 b0 a2  80 00 00 00 ff ff ff ff   ··l····· ········
0020  ff ff 00 00 00 00 00 02  00 00 00 00 00 02 00 00   ········ ········
0030  85 8c 01 00 00 00 00 00  64 00 01 00 00 0c 77 69   ········ d·····wi
0040  66 69 2d 64 65 66 61 75  6c 74 01 04 82 84 0b 16   fi-defau lt······
0050  03 01 01 00 00 00 00                               ·······
```

Wi-Fi MAC operation overview



Note: Multi-Link Operation (not depicted) results in more instances of CAM, FEM, Wifi Remote Station Manager, and PHYs

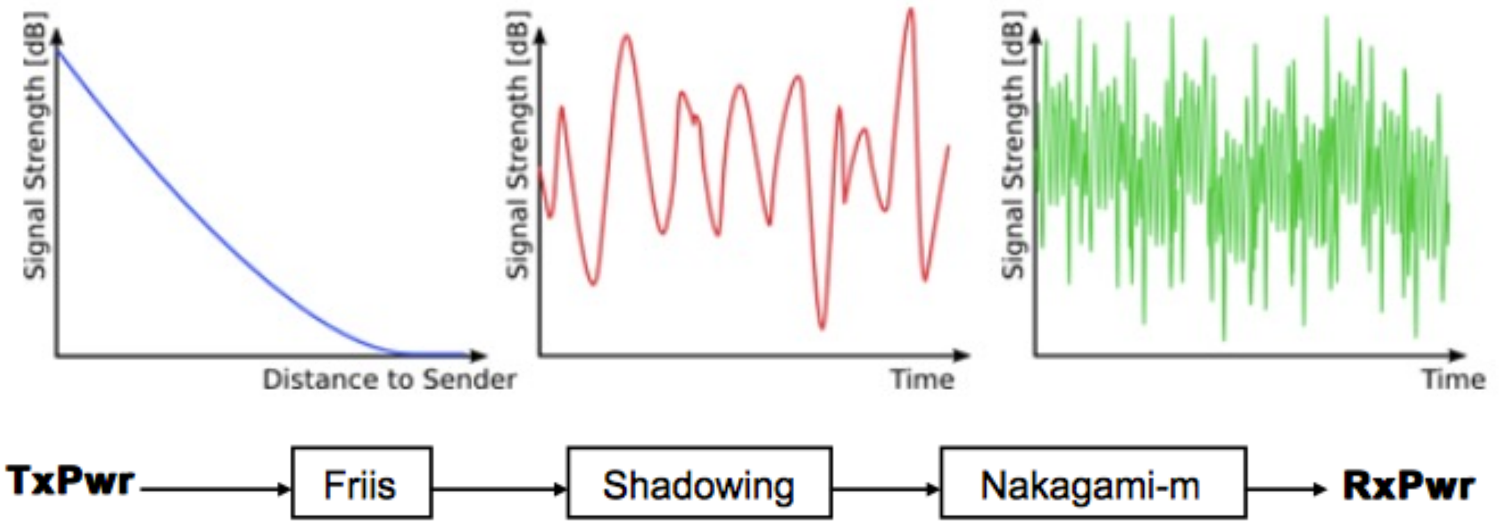
Overview of ns-3 PHY PPDU TX and RX operations



Note: Multi-Link Operation (not depicted) results in more instances of WifiPhy(s) and links/channels

Overview of ns-3 Wi-Fi channel operation

Figure source: Unknown



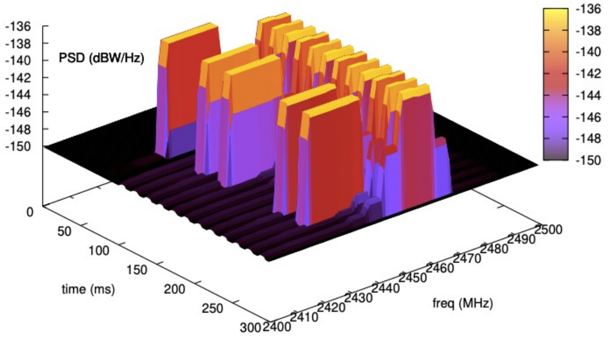


Fig. 1: Spectrogram produced by a spectrum analyzer in a scenario involving wifi signals interfered by a microwave oven, as simulated by the example `adhoc-aloha-ideal-phy-with-microwave-oven`.

SpectrumValue representation (power in bands)

SpectrumChannel option:

- Necessary for OFDMA
- Multi-model spectrum channel for most cases
- Facilitates coexistence (NR-U)
- Possibility to use 3GPP propagation models
- Possibility to use 3GPP antenna models

Figure sources: ns-3 documentation

Recent additions

ns-3.38 release, March 2023

- 802.11be **Multi-Link Operations (MLO), STR mode** only
- **EHT Capabilities** information element improvements
- 802.11ax **dual NAV** (basic NAV and intra-BSS NAV)
- 802.11ax **Uplink Multi-User Carrier Sense (UL MU CS)** mechanism and have it used by non-AP STAs when determining if they can reply to a received Trigger Frame
- 802.11ax **MU-RTS/CTS protection**
- Initial 802.11be-based example program

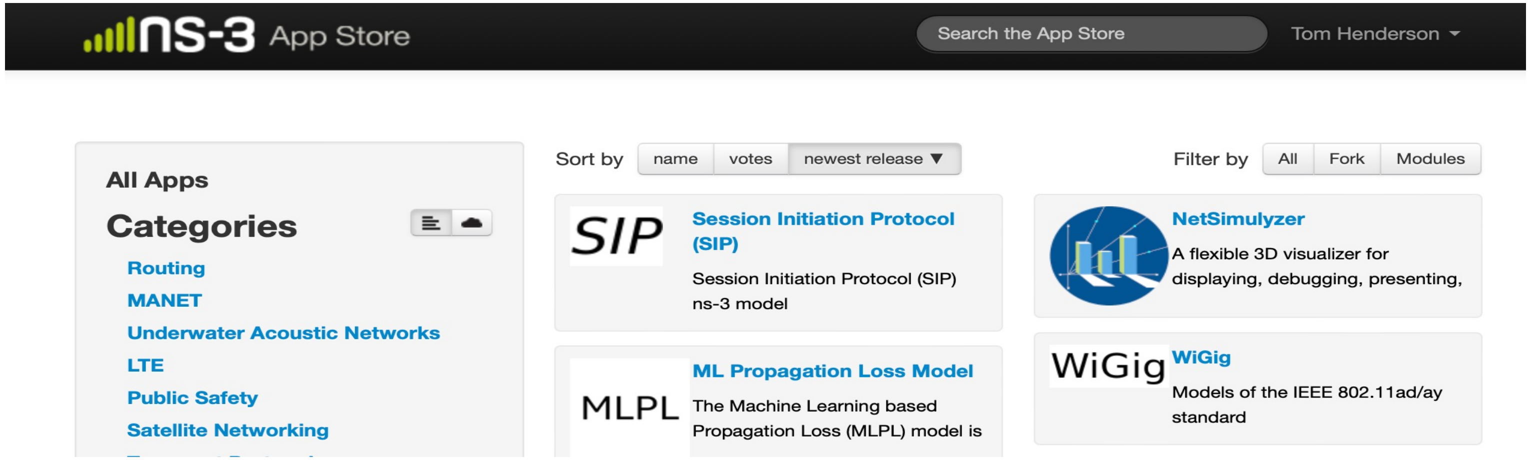
ns-3.39 release, July 2023

- No major feature additions for 802.11ax/be

Recent additions

ns-3.40 release, September 2023

- Added support for multi-radio **Multi-link operation** (MLO)
  - Support for 802.11be TID-to-Link Mapping
  - Additional PHY support for multiple interfaces and switching
- Added initial support for **MU-MIMO** (ideal PHY layer only)
- Refactored 802.11ad model (**WiGig**) as an ns-3 extension module in the ns-3 App Store



Recent additions

ns-3.41 release, January 2024

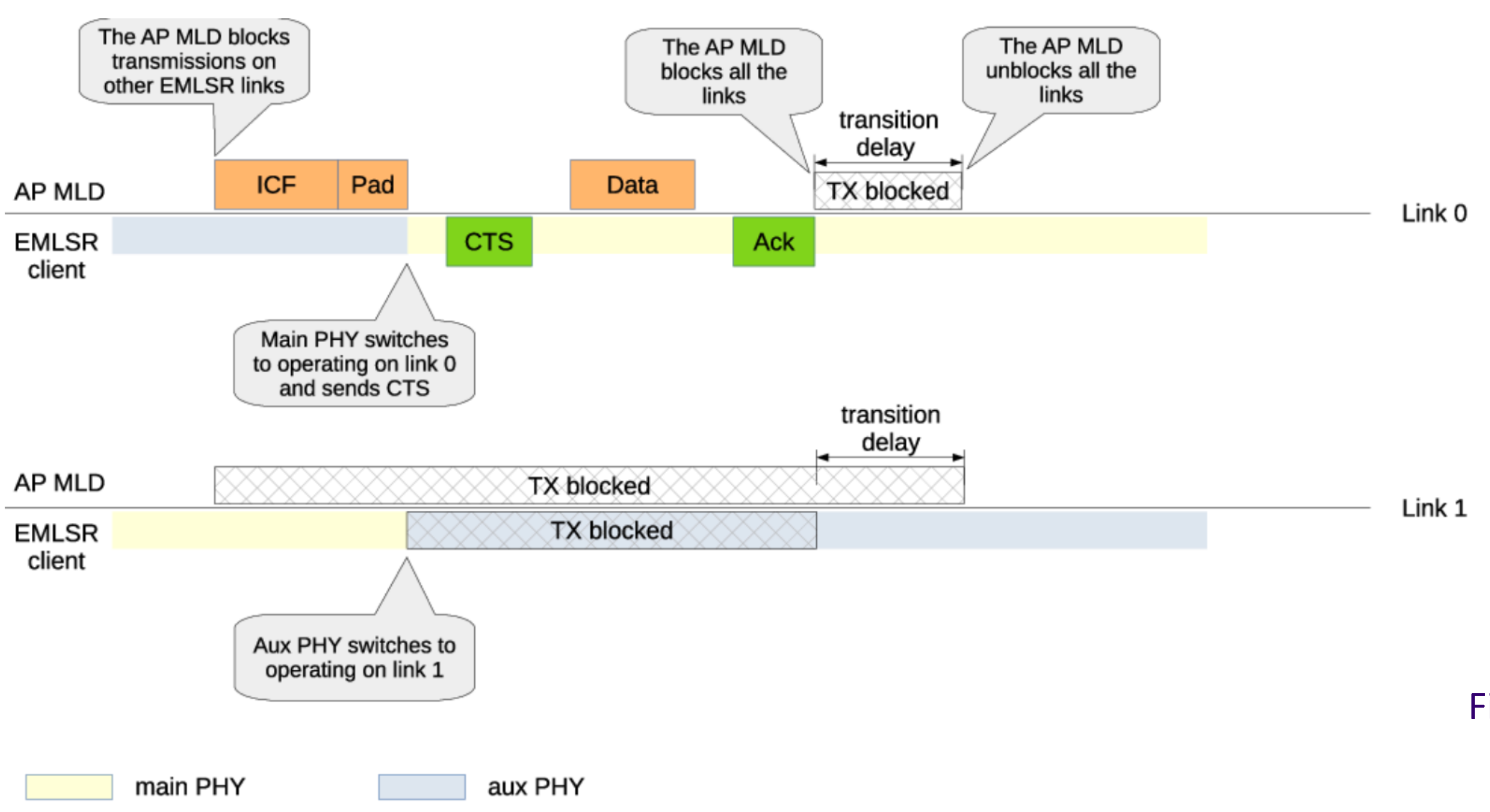
- Complete support for **Enhanced Multi-link Single Radio (EMLSR)** mode of MLO
  - can support reduced functionality auxiliary radios for sensing, RTS/CTS transmissions

ns-3.42 release, May 2024

- **WifiPhyRxTraceHelper**
- More EMLSR fixes/improvements
- Operations in the 6 GHz band
- Rework attributes to set EDCA parameters

EMLSR in ns-3

> Use of a single full function radio with other reduced function radios for monitoring other links



EMLSR operations: Downlink TXOP

Figure courtesy of Stefano Avallone

WifiPhyRxTraceHelper

> Fine-grained tracking of all PPDU and MPDU reception events and outcomes, with emphasis on **signal overlaps**

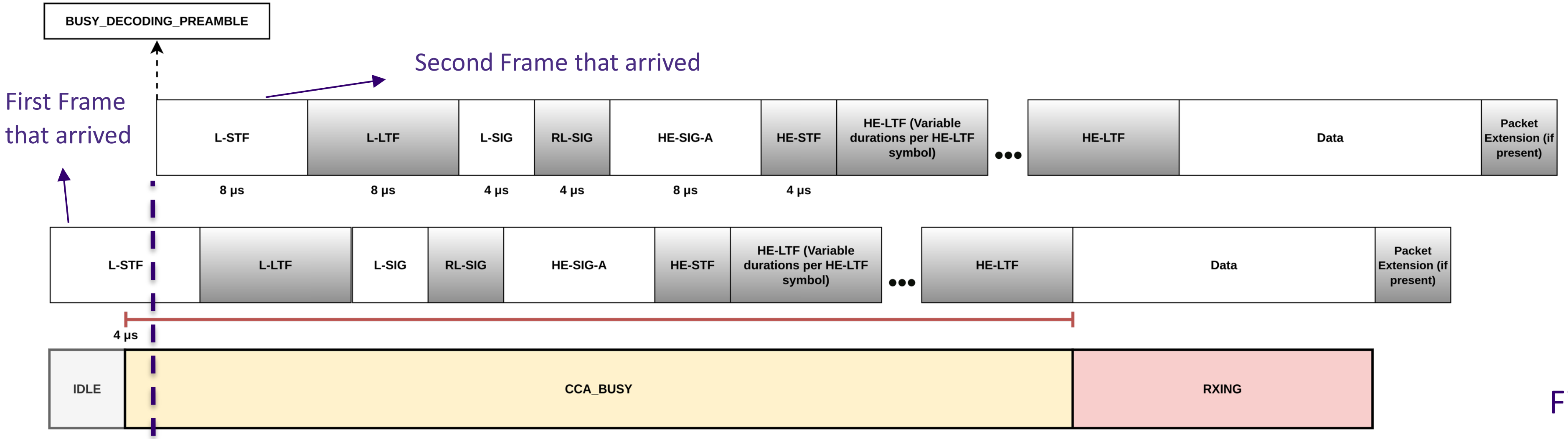


Figure courtesy of Juan Leon

WifiPhyRxTraceHelper

> Based on a time window of interest, the API supports **printing of statistics** at the granularity of an MLO link, or aggregated from a node container, all nodes, all links
  - Sample built-in output from example program:

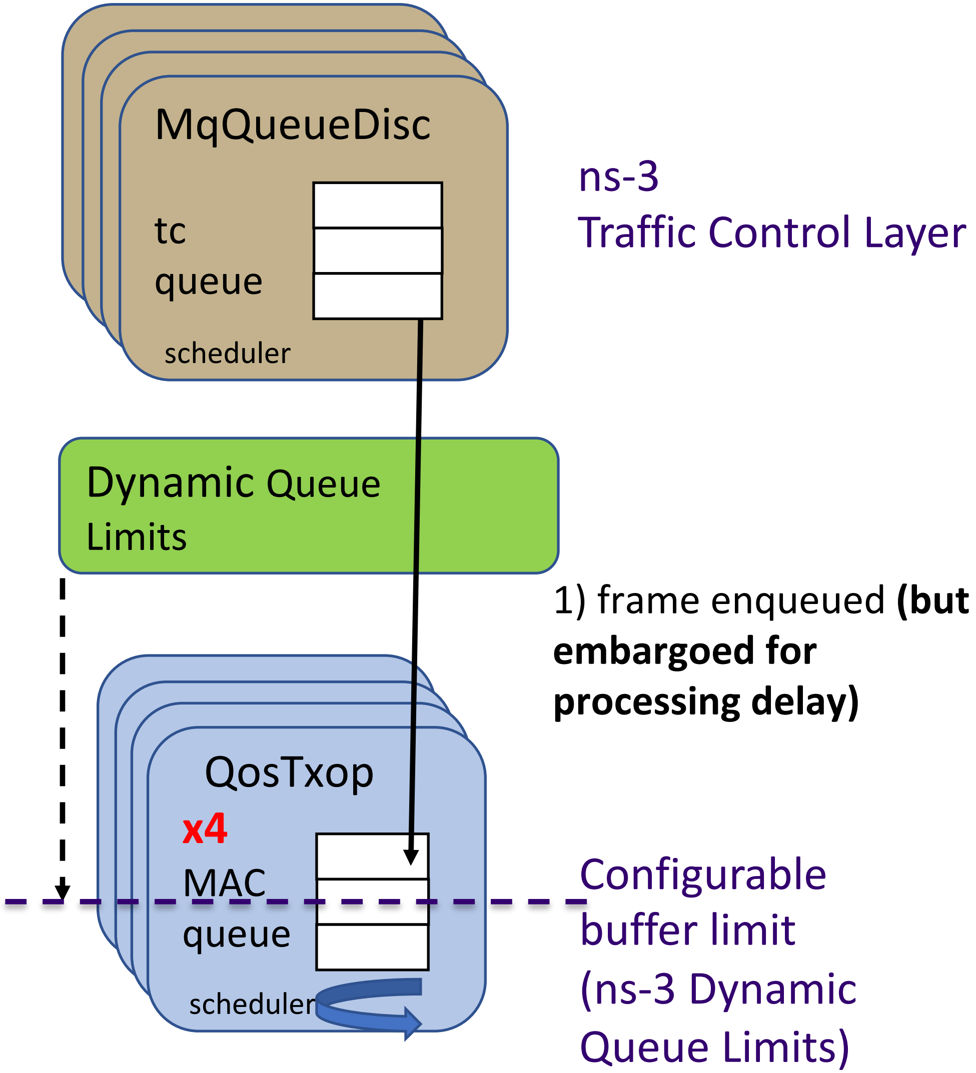
```
Total PPDUs Received: 1
Total Non-Overlapping PPDUs Received: 1
Total Overlapping PPDUs Received: 0

Successful PPDUs: 1
Failed PPDUs: 0

Total MPDUs: 1
Total Successful MPDUs: 1
Total Failed MPDUs: 0
```

> The API also supports **exporting access to the full trace records**, with similar granularity

Future planned work (Tom Henderson)

- Features of interest
  - Support for Wi-Fi **dynamic queue limits** and **processing delay**
  - Shepherd **additional trace helpers**, currently in progress (!2004, !2009)
  - Shepherd **CSI exchange protocol** (merge request !1775)
  - Stochastic models for **fading channels**
  - Stochastic models for **preamble and energy detection**
  - Finish Sandia Laboratories **signal clipping** patches
  - Reference scenarios from **TGAX Simulation Scenarios**
- Unfunded; looking to collaborate/mentor
  - **Packet lifecycle** and **packet drop tracing**
  - **Example curation**, **helper additions**, and **logging curation**
  - Detailed **Wi-Fi example tutorial** similar to 5G NR cttc-nr-demo tutorial
  - **Educationally-oriented** examples and visualizations
  - **Minstrel-HT rate control updates** (and other rate controls)
  - A few unaddressed bugs (#289, #851, #1010)

Support for Wi-Fi dynamic queue limits and proc. delay



Additional trace helpers in progress (ns-3.43 target)

> **WifiCoHelper** (channel occupancy) – from IIIT-Delhi (Puneet Kumar, Jagrati Kulshrestha, Mukulika Maity)
  - Will be useful for airtime fairness statistics

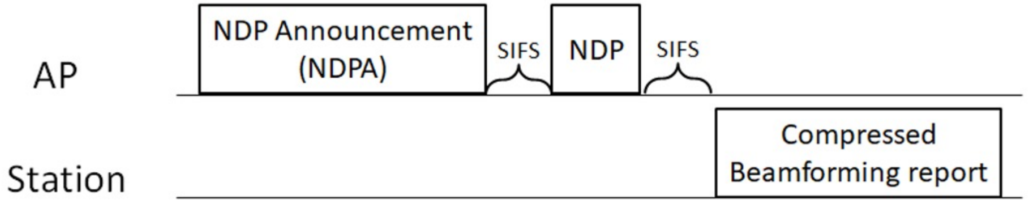
```
---- COT for STA_0----
Showing duration by states:
IDLE: 328 ms
CCA_BUSY: 85 ms
TX: 98 ms
RX: 9564 ms

---- COT for AP----
Showing duration by states:
IDLE: 328 ms
CCA_BUSY: 30 ms
TX: 9662 ms
RX: 60 ms
```

> **WifiMacTxStatsHelper** from Muyuan Shen at HUST
  - Detailed trace of MPDU transmit/retransmission outcomes

CSI exchange protocol

> Currently missing a PHY abstraction

- **Channel Sounding in IEEE 802.11ax**
  - Single-user case:



  - Multi-user case:

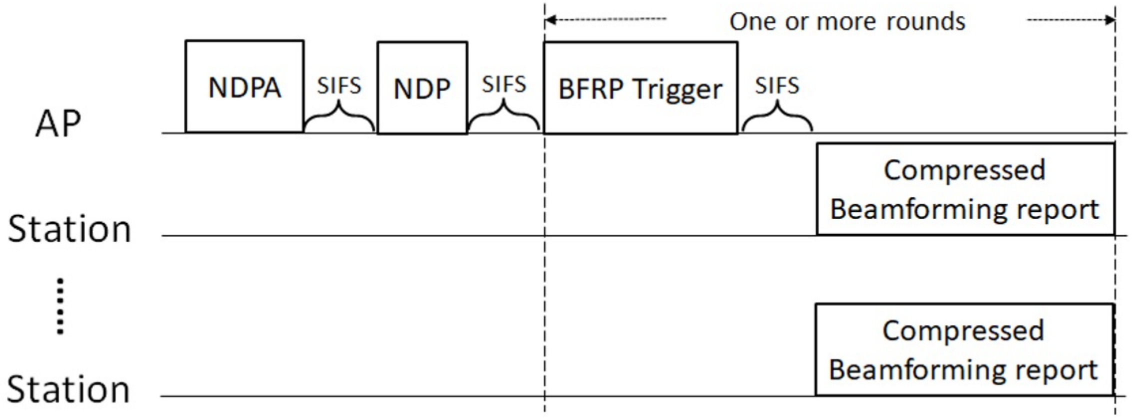


Figure source: Jingyuan Zhang

Support for fading channels

Complete link-to-system mapping error models for TGn channel model D for DL 4x2:2, UL 2x4:2 SU MIMO channels

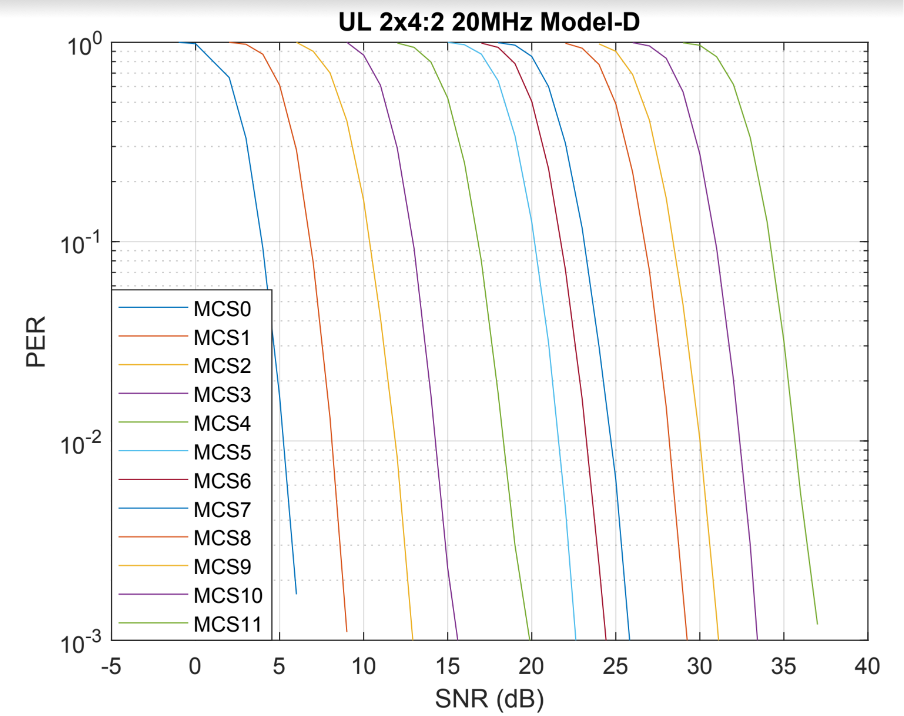
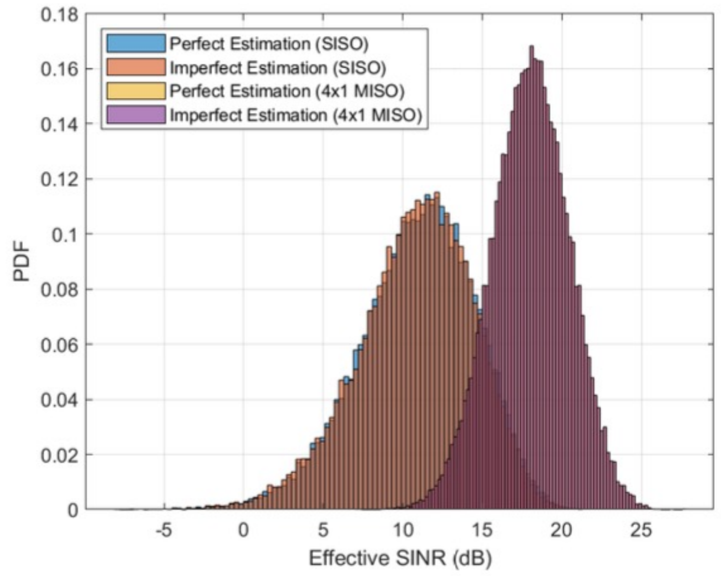


Figure courtesy of Liu Cao

Space-efficient representations of fading model error rate curves as log-SGN parameterized distributions

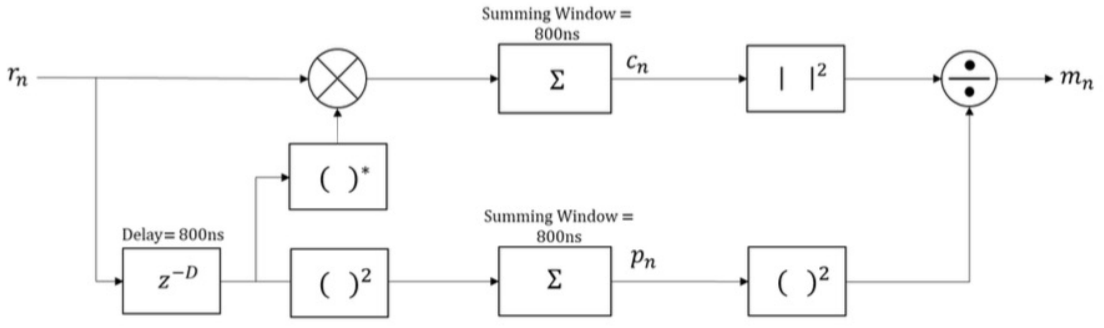


An example fitted log-SGN distribution (Figure 5 of below paper reference)

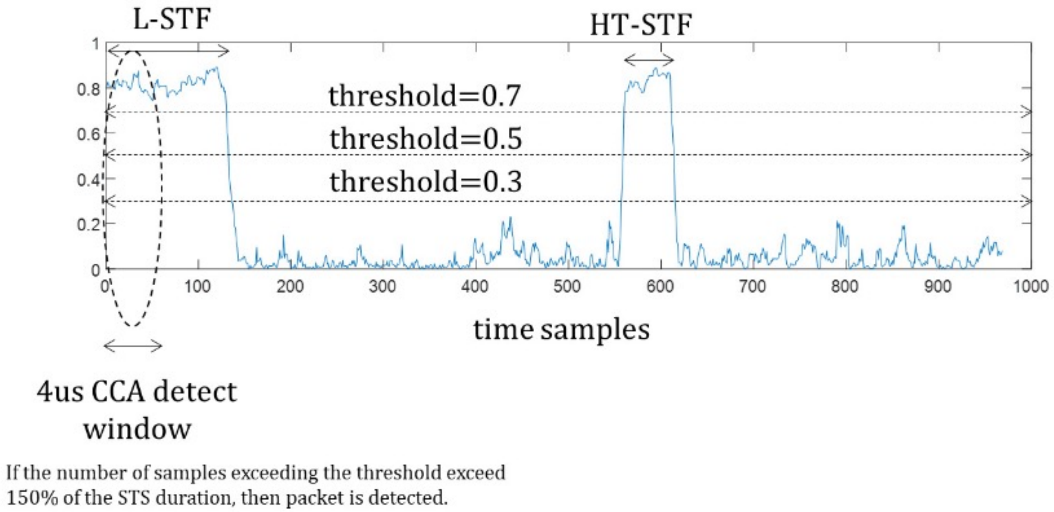
L. Cao, L. Zhang, S. Jin and S. Roy, "Efficient MIMO PHY Abstraction With Imperfect CSI for Fast Simulations," in IEEE Wireless Communications Letters, vol. 12, no. 3, pp. 530-534, March 2023.

Stochastic models for preamble and energy detection

Stochastic signal detect (CCA-SD) and energy detect (CCA-ED) models based on MATLAB WLAN Toolbox simulations



Preamble Normalized Correlation Block
(Figure 5 from reference below)



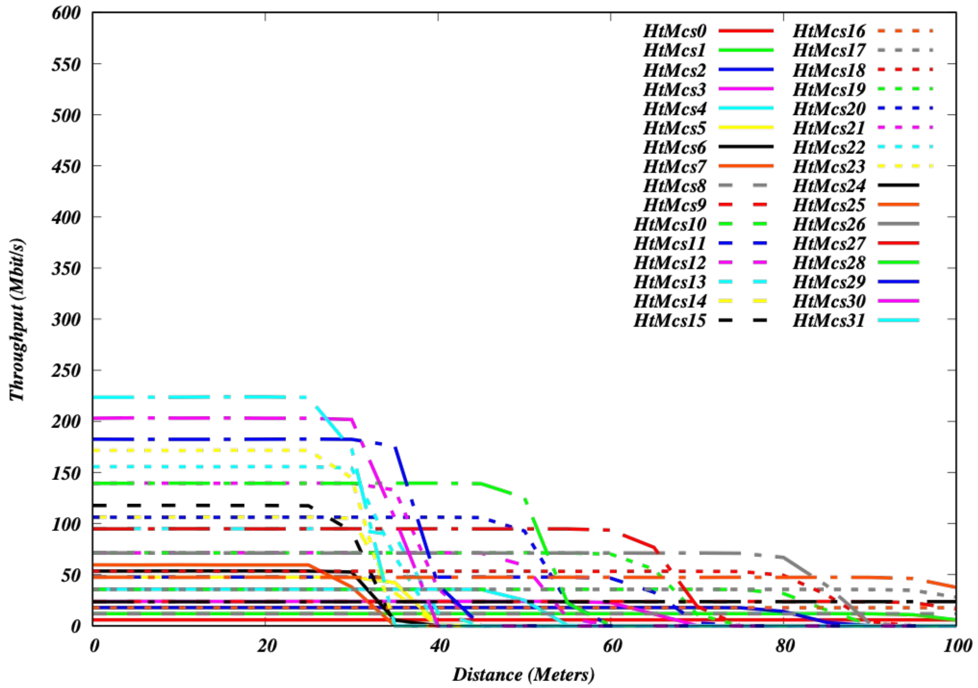
Normalized Correlation of 802.11 Preamble
(Figure 6 from reference below)

Leonardo Lanante, Sumit Roy, Scott E. Carpenter, and Sébastien Deronne. 2019. Improved Abstraction for Clear Channel Assessment in ns-3 802.11 WLAN Model. In Proceedings of the 2019 Workshop on ns-3 (WNS3 '19). Association for Computing Machinery, New York, NY, USA, 49–56.

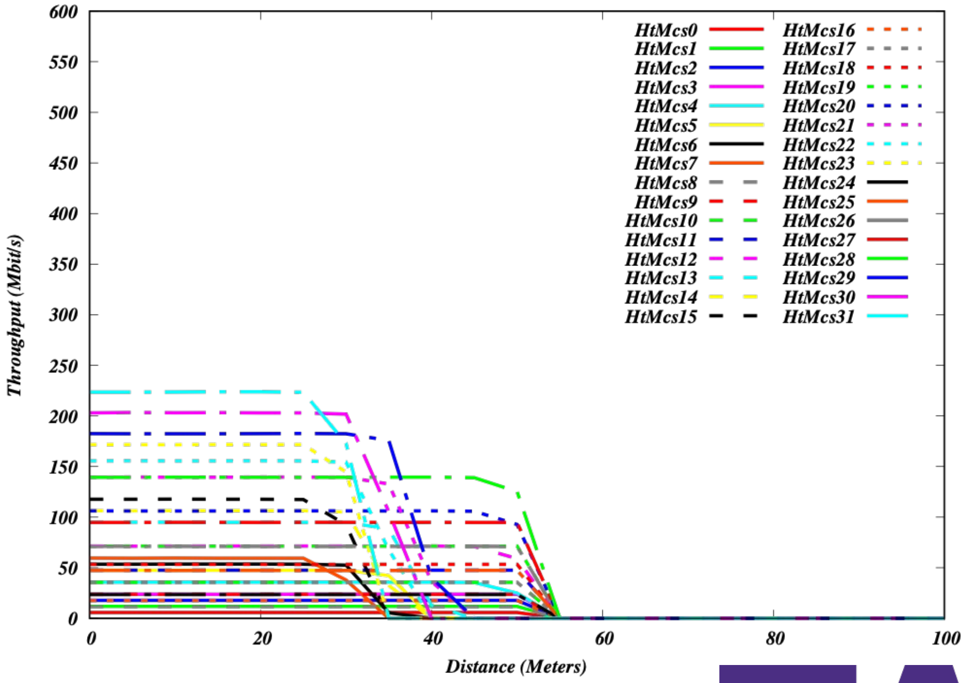
PHY receive sensitivity

> Industry feedback: Can receive frames below -82 dBm RSSI (20 MHz)

```
./ns3 run 'wifi-80211n-mimo --preambleDetection=0'
```

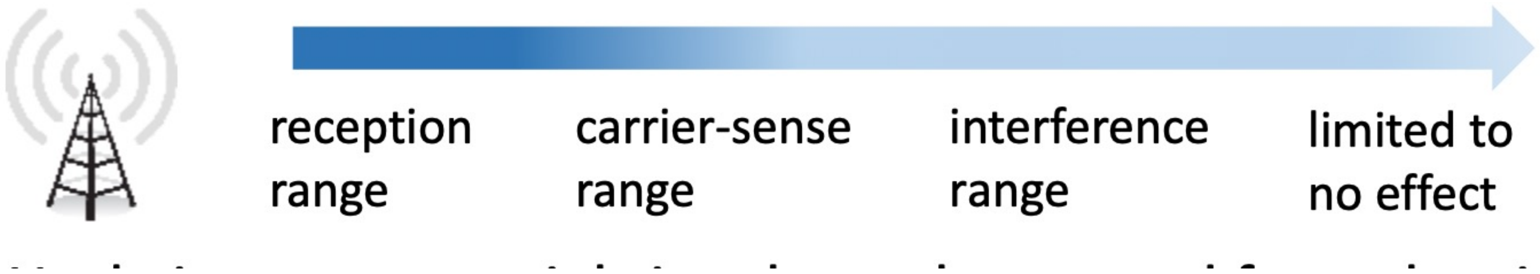



```
./ns3 run 'wifi-80211n-mimo --preambleDetection=1'
```



Upcoming PHY abstraction support (cont.)

Write tests to validate Sandia National Laboratory's signal clipping support



Prune simulation events corresponding to very weak signals

How to efficiently maintain/query data structures of what would be weak?

Sandia National Laboratories proposed:

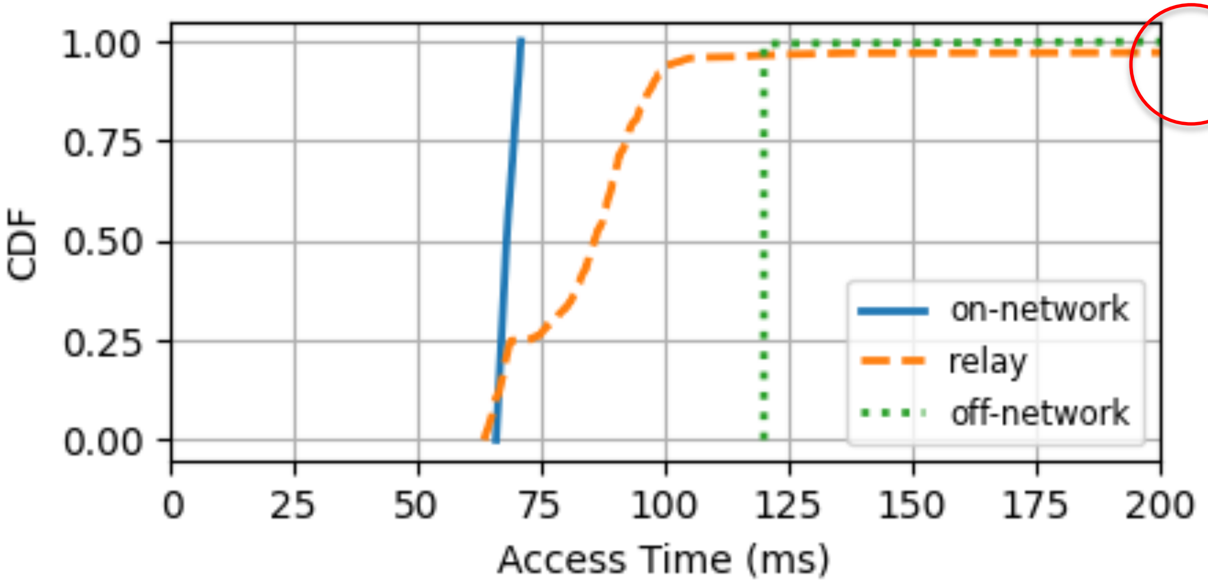
- A k-d tree stores the position for each node
- A min-heap stores for each node a time at which the node will be displaced beyond *rD* from the k-d tree position

A. Ganti, U. Onunkwo, B. Van Leeuwen, M. P. Scoggin and R. Schroeppel, "A Novel Approach to Exponential Speedup of Simulation Events in Wireless Networks," 2018 International Conference on Computing, Networking and Communications (ICNC), Maui, HI, USA, 2018.

Packet lifecycle and packet drop tracing

> What happened to certain packets?

Excessive latency?




```
Flow 1 (1.0.0.2:49153 -> 7.0.0.2:1234) proto UDP
    Tx Packets: 6000
    Tx Bytes:   768000
    TxOffered:  10.240000 Mbps
    Rx Bytes:   767744
    Throughput: 10.236587 Mbps
    Mean delay:  0.271518 ms
    Mean jitter:  0.030032 ms
    Rx Packets: 5998
```

Where were these two packets lost?

Future planned work (Sebastien Deronne/Stefano Avallone)

- **802.11be EMLSR**
- **80+80 MHz**
- **Groupcast with retries**: GCR-UR and GCR-BA
- **Power save** modes
- **EHT RU and MRU** (and finalize support for **preamble puncturing**)
- **320 MHz** channel width
- **802.11bn** (Wi-Fi 8)
- **TWT** (Target Wake Time)

Future modeling priorities? Industry requests?

> Better AP model? Per-STA queue limits are lacking
> Seamless roaming (legacy, and multi-link roaming?)
> Deterministic operation
> Wi-Fi preemption
> Return of OBSS-PD mechanisms in Wi-Fi 8
> New ICF/ICR control exchange (supporting quick BSRs, …)
> Millimeter wave support?