

## COEXISTENCE OF WIFI AND LAA: CDF RESULTS

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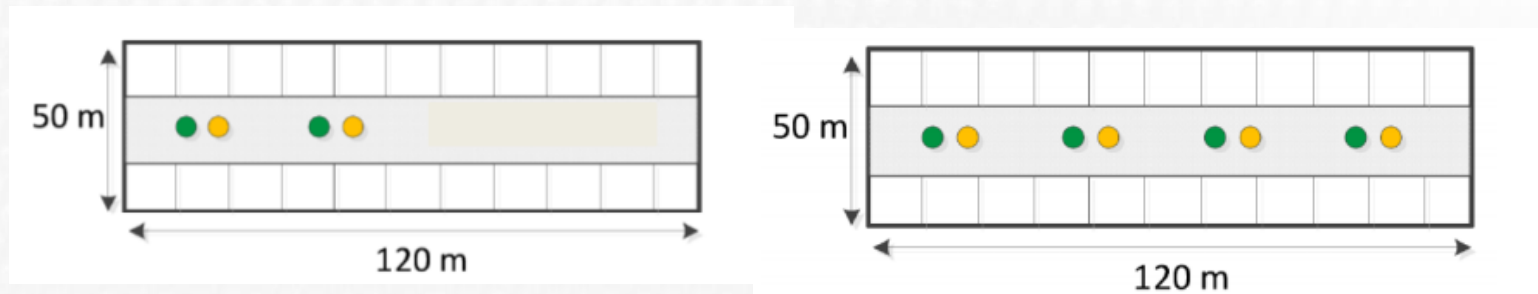
# Outline

- ❖ Problem Review
- ❖ CDF Results
  - Case II
  - Single user
  - Multiple users
- ❖ Simulation Results from NS-3
- ❖ Next Step

# Problem Review

## ❖ Simulation Setting

- ✓ 4 pairs or 8 pairs



- ✓ Load ratio: 0.2/0.5/0.8
- ✓ LAA energy detection threshold: -65/-70/-75 dBm
- ✓ Definitions of delay: I) delay = [time of successful transmission – time of arrival];  
II) delay = [time of successful receiving – time of ready to be transmitted];

# CDF Results: Case II

## ❖ Percentage of time occupation, 4 pairs

### ✓ Load ratio of 0.8

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.8041	0.8870	0.4019	0.4022	0.4450	0.4420
-70	0.8226	0.5079	0.4474	0.3752	0.0639	0.4440
-75	0.8955	0.0144	0.4455	0.4500	0.0066	0.0078

### ✓ Load ratio of 0.5

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.6634	0.6642	0.3330	0.3303	0.3314	0.3329
-70	0.6654	0.5350	0.3321	0.3333	0.2023	0.3327
-75	0.6663	0.2021	0.3334	0.3329	0.1014	0.1007

### ✓ Load ratio of 0.2

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.3313	0.3348	0.1659	0.1654	0.1663	0.1685
-70	0.3347	0.3309	0.1675	0.1672	0.1653	0.1656
-75	0.3337	0.3342	0.1671	0.1666	0.1665	0.1677

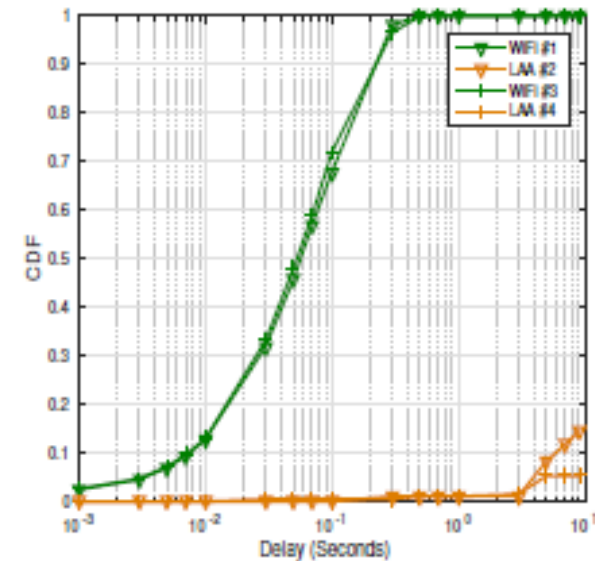
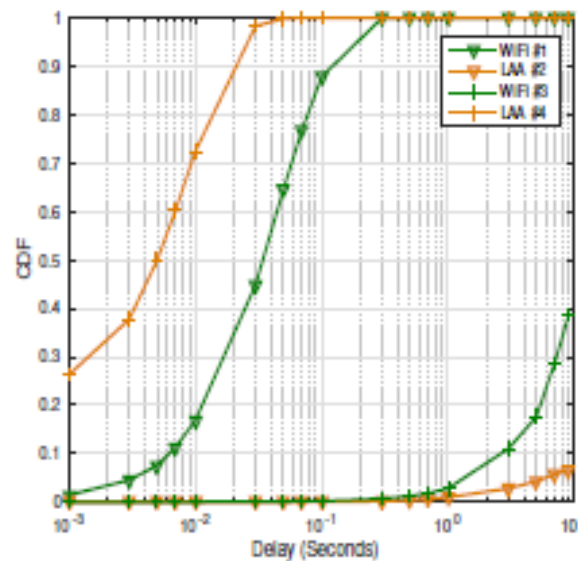
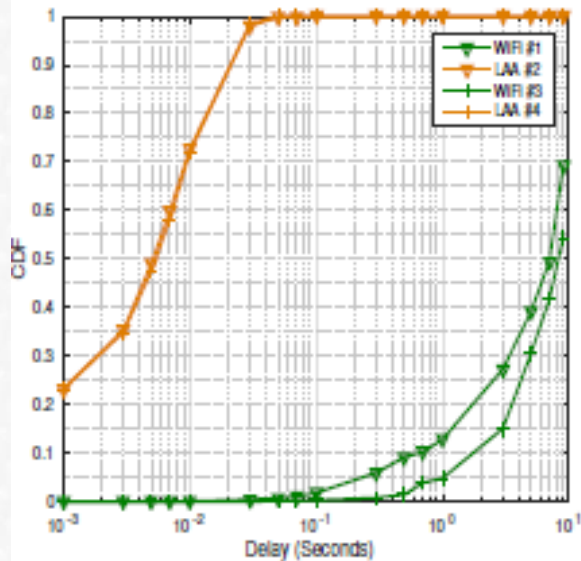
At a low load ratio (0.2), there is not too much competition between WiFi and LAA.

# CDF Results: Case II

## ❖ Delay with Definition I, 4 pairs

✓ Load ratio of 0.8 (in sec)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	7.1194	0.0073	6.5686	7.6698	0.0073	0.0073
-70	5.3989	7.9872	0.0472	11.6686	64.4340	0.0072
-75	0.0815	78.0867	0.0829	0.0801	76.9641	79.1500



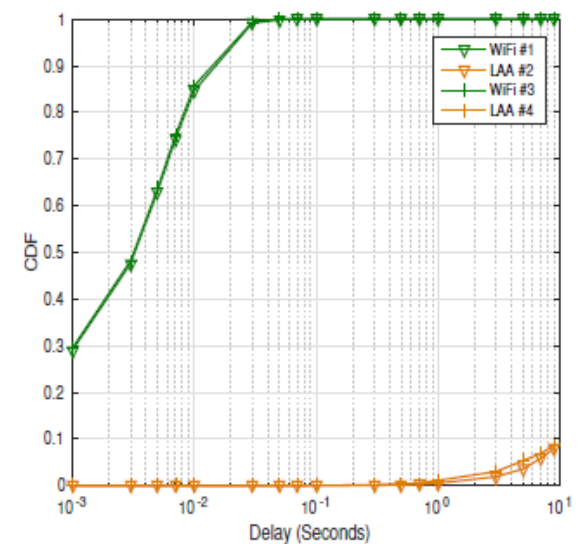
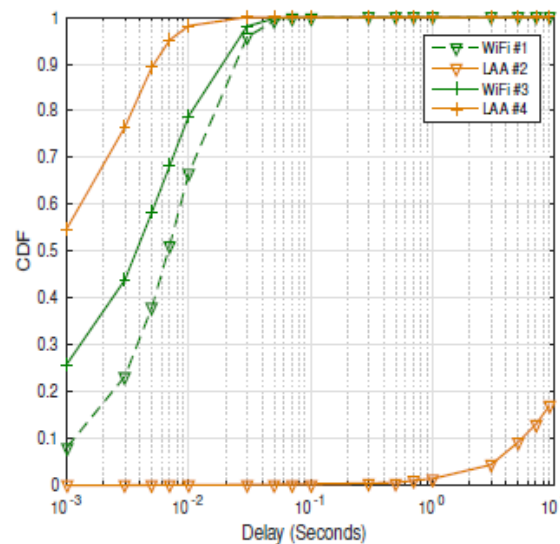
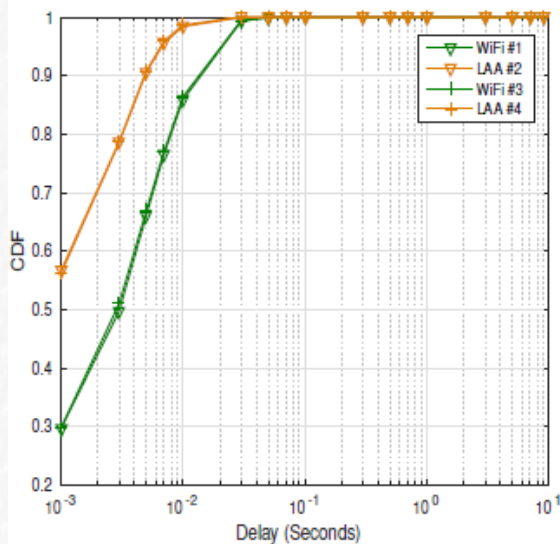
In -70 dBm and -75 dBm, collisions may happen frequently in this case due to asymmetric threshold for energy detection. (Note: the X-axis is in log scale.)

# CDF Results: Case II

## ❖ Delay with Definition I, 4 pairs

✓ Load ratio of 0.5 (in sec)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.0048	0.0017	0.0048	0.0047	0.0017	0.0017
-70	0.0079	10.8458	0.0095	0.0063	28.6761	0.0018
-75	0.0050	51.9697	0.0051	0.0049	52.3055	51.6315



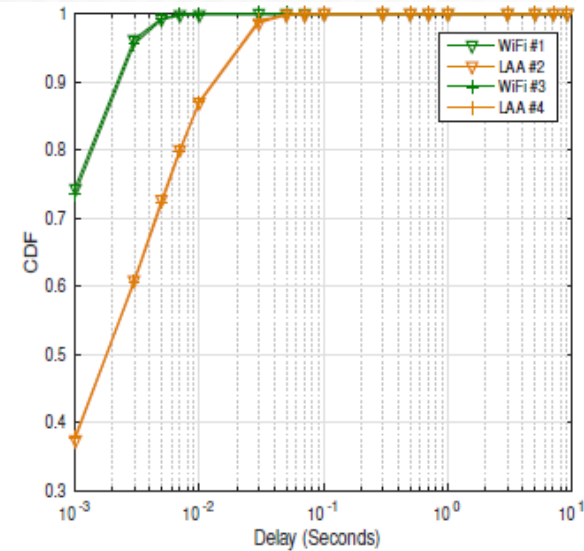
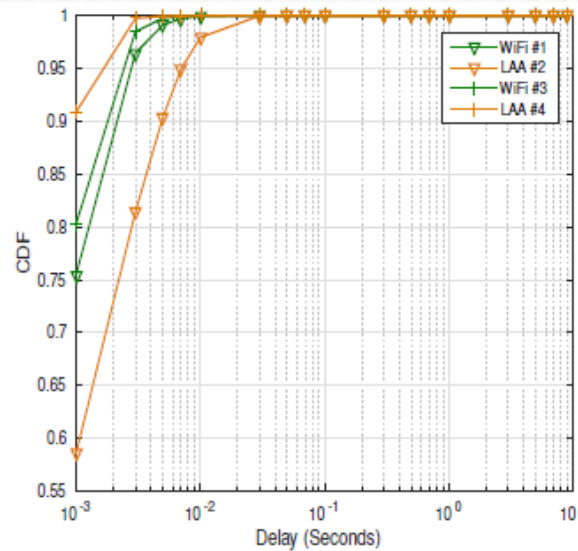
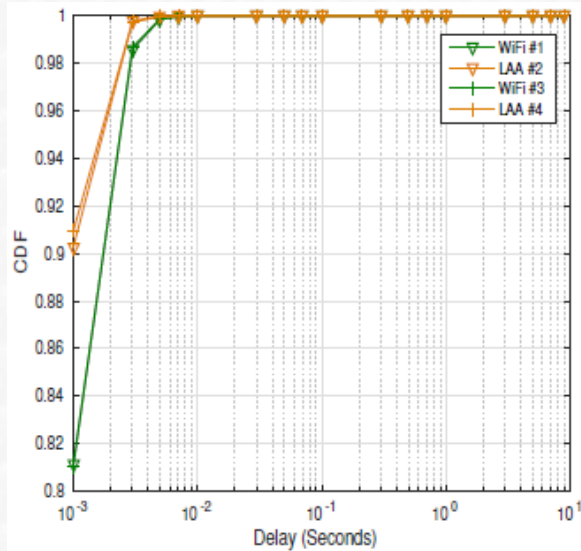
WiFi: worse → middle → better

# CDF Results: Case II

## ❖ Delay with Definition I, 4 pairs

✓ Load ratio of 0.2 (in msec)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.4534	0.2324	0.4529	0.4539	0.2363	0.2286
-70	0.5540	0.9462	0.6366	0.4711	1.6645	0.2292
-75	0.6679	4.3500	0.6510	0.6849	4.3825	4.3177



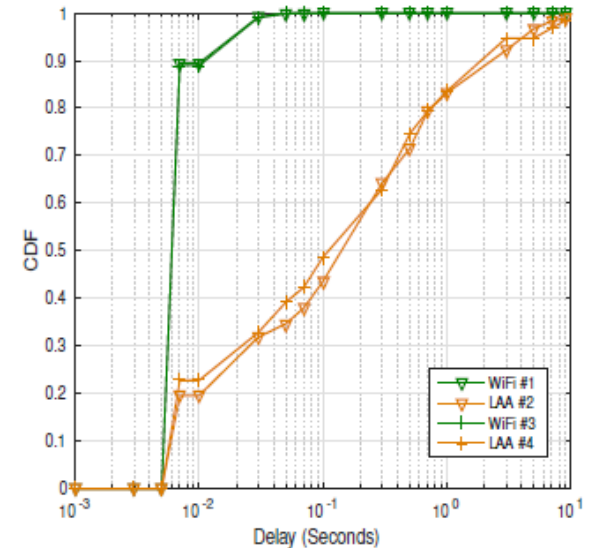
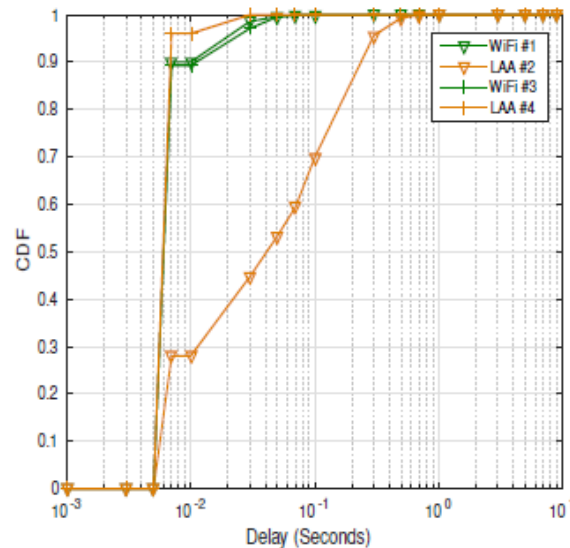
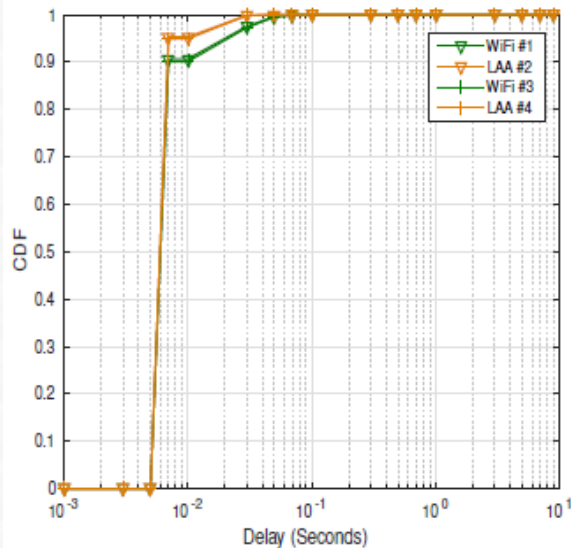
At a low load ratio (0.2), LAA and WiFi almost have the same performance.

# CDF Results: Case II

## ❖ Delay with Definition II, 4 pairs

✓ Load ratio of 0.8 (in sec)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.0075	0.0062	0.0075	0.0076	0.0062	0.0062
-70	0.0075	0.0157	0.0073	0.0078	0.0840	0.0060
-75	0.0071	0.7990	0.0071	0.0072	0.8223	0.7769



Similar trend. WiFi keeps the same: WiFi transmit first, not a problem; LAA transmit first, collisions to LAA.

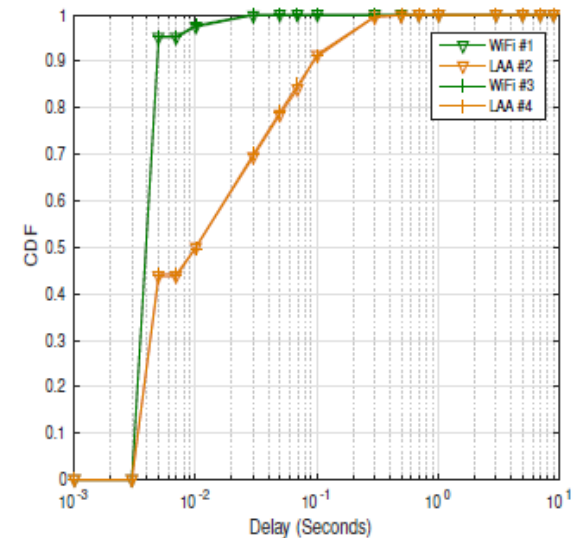
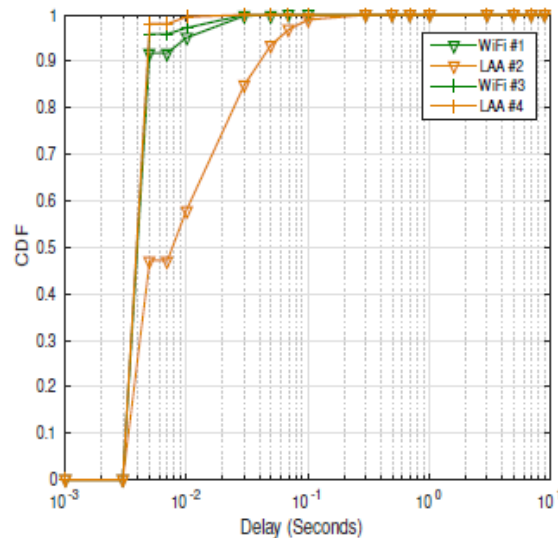
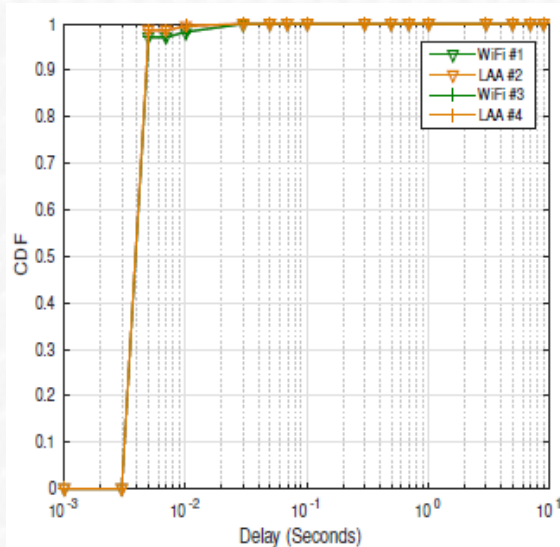


# CDF Results: Case II

## ❖ Delay with Definition II, 4 pairs

✓ Load ratio of 0.5 (in sec)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.0038	0.0038	0.0038	0.0038	0.0037	0.0036
-70	0.0041	0.0082	0.0043	0.0040	0.0156	0.0037
-75	0.0039	0.0326	0.0039	0.0039	0.0325	0.0327

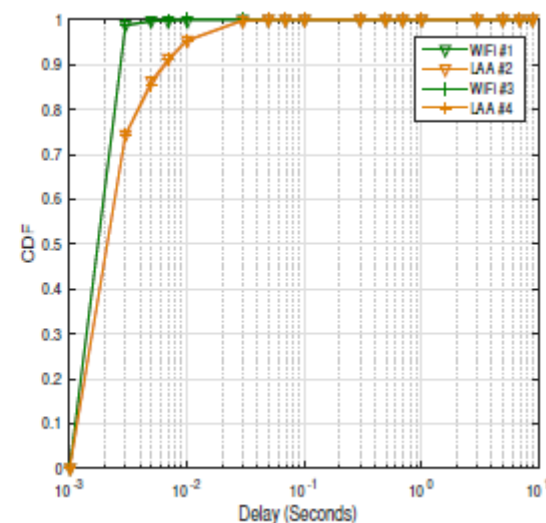
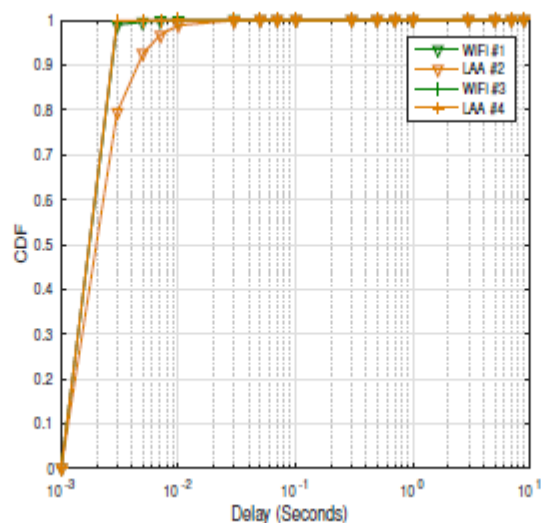
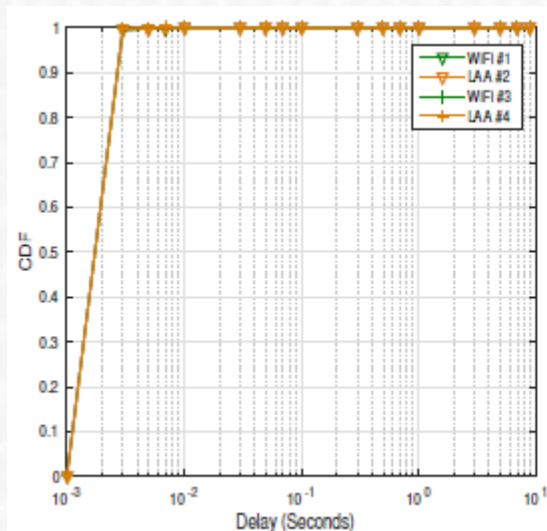


# CDF Results: Case II

## ❖ Delay with Definition II, 4 pairs

✓ Load ratio of 0.2 (in sec)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014
-70	0.0014	0.0018	0.0015	0.0014	0.0022	0.0014
-75	0.0015	0.0029	0.0015	0.0015	0.0029	0.0029



# CDF Results: Single User, 4 Transmitters

## ❖ Percentage of time occupation

✓ Load ratio of 0.8

- Average percentage of time occupation

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.5264	0.6503	0.3264	0.2000	0.2859	0.3644
-70	0.5547	0.6106	0.2795	0.2752	0.2740	0.3366
-75	0.6210	0.5208	0.3523	0.2687	0.2247	0.2961

- “Average” percentage of time occupation (excluding bad locations)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.5478	0.7851	0.3415	0.2063	0.3808	0.4043
-70	0.5377	0.7646	0.2809	0.2568	0.3574	0.4072
-75	0.6047	0.5809	0.3435	0.2611	0.2760	0.3049

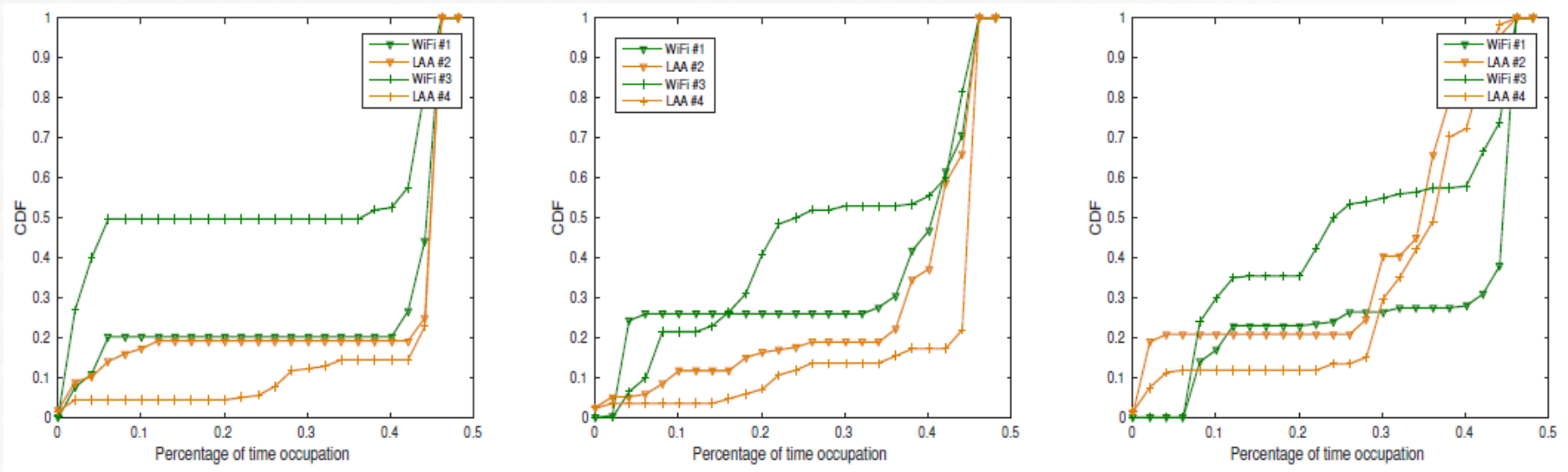
Should we exclude bad locations?

# CDF Results: Single User, 4 Transmitters

## ❖ Percentage of time occupation

✓ Load ratio of 0.8

- CDF



From -65 to -75 dBm, WiFi is improving in general. The probability for low percentage of time occupation (for example, less than 0.1) is decreasing.

# CDF Results: Single User, 4 Transmitters

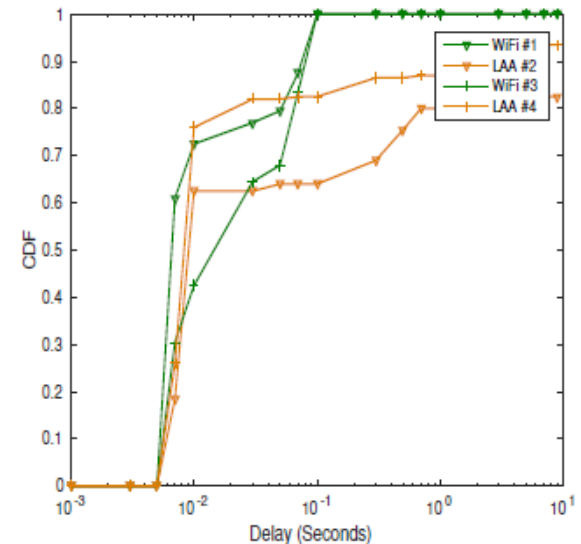
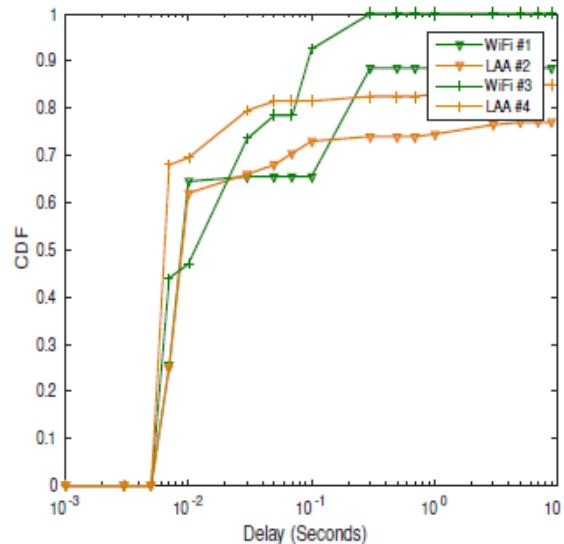
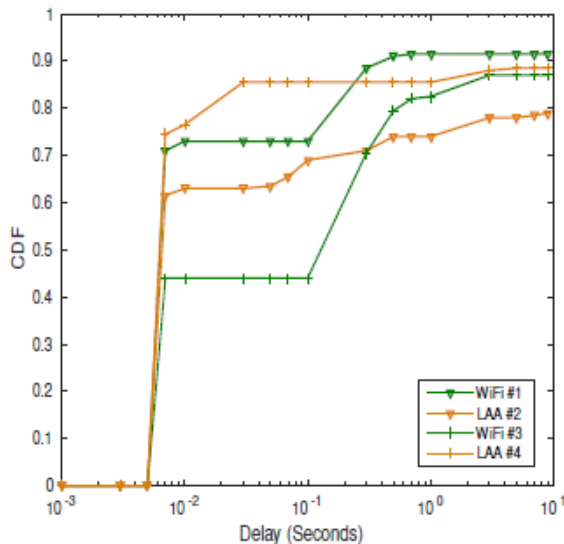
## ❖ Delay with Definition II

✓ Load ratio of 0.8

- “Average” delay (excluding bad locations)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.1190	0.2822	0.0579	0.1800	0.2159	0.3485
-70	0.0552	0.0877	0.0315	0.0093	0.0188	0.0205
-75	0.0294	0.1851	0.0232	0.0356	0.1390	0.2313

- CDF



WiFi is improving in general. The probability of large delay is decreasing.

# CDF Results: Single User, 4 Transmitters

## ❖ Percentage of time occupation

✓ Load ratio of 0.5

- Average percentage of time occupation

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.4354	0.4810	0.2645	0.1709	0.2197	0.2614
-70	0.5286	0.4603	0.2563	0.2723	0.2142	0.2461
-75	0.5537	0.4347	0.2827	0.2710	0.2136	0.2210

- “Average” percentage of time occupation (excluding bad locations)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.5022	0.5811	0.2811	0.2211	0.2942	0.2869
-70	0.5439	0.5567	0.2706	0.2733	0.2685	0.2882
-75	0.5516	0.5356	0.2831	0.2686	0.2398	0.2959

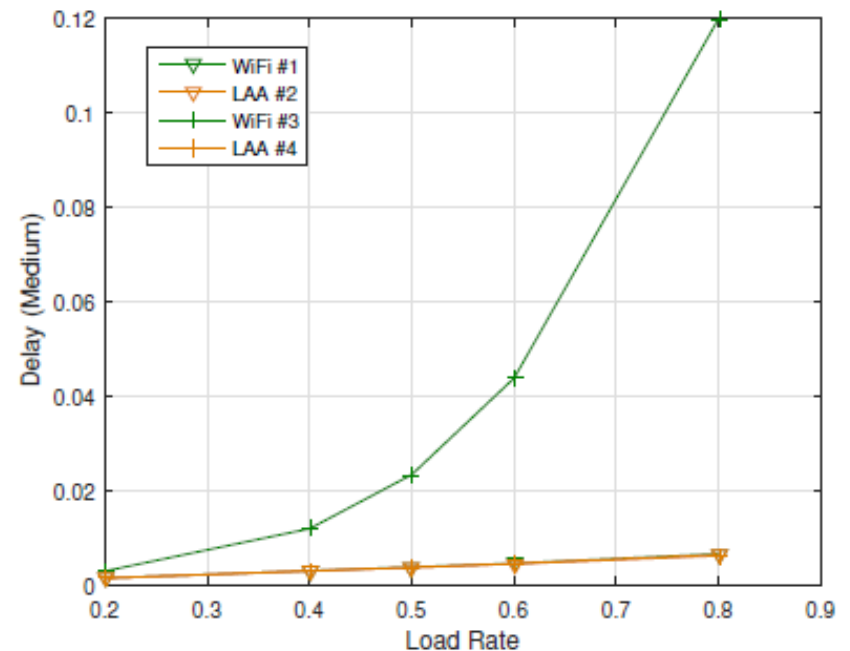
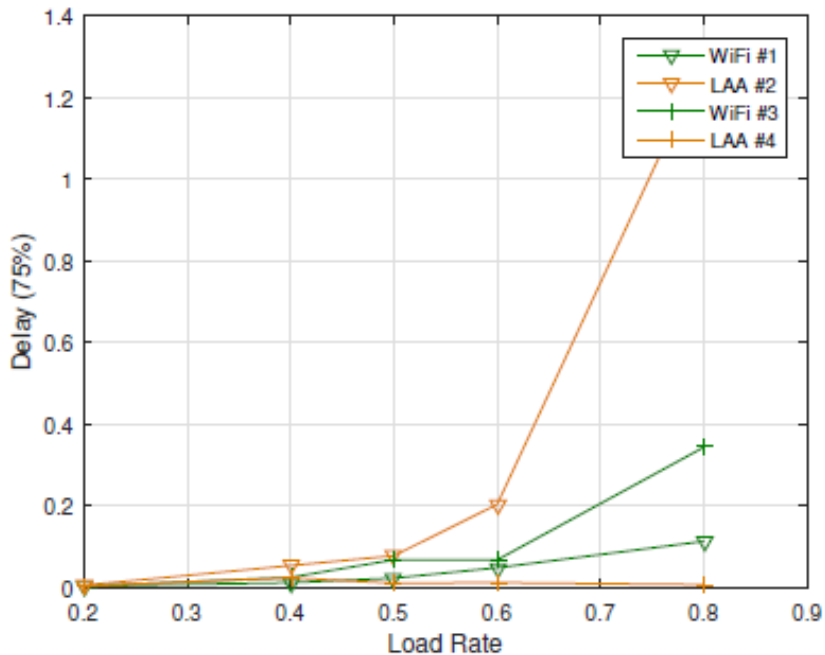
- “Average” delay (excluding bad locations)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	LAA (#2)	LAA (#4)
-65	0.0243	0.0144	0.0115	0.0371	0.0119	0.0169
-70	0.0204	0.0197	0.0315	0.0093	0.0188	0.0205
-75	0.0098	0.0336	0.0089	0.0106	0.0465	0.0206

# CDF Results: Single User, 4 Transmitters

## ❖ Delay versus Load ratio

✓ LAA ED: -65 dB

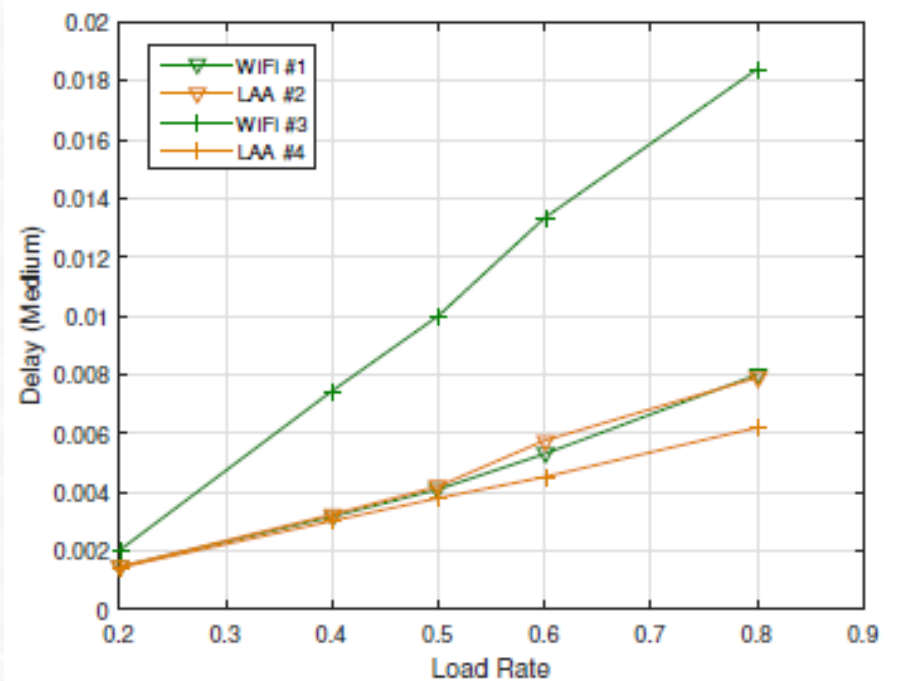
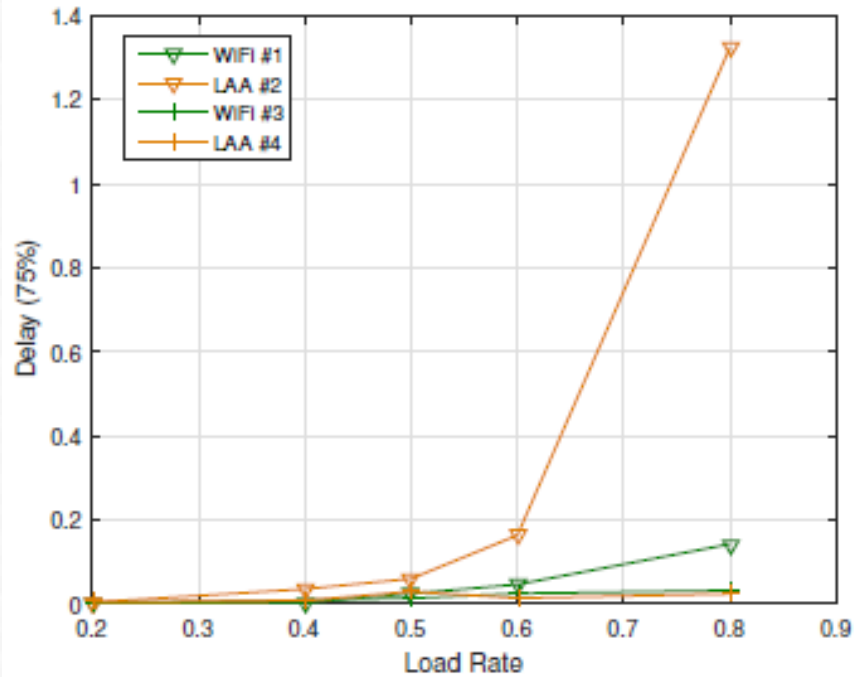


Different trend for the 75<sup>th</sup>-percentile and medium? Note: different scale in Y-axis.

# CDF Results: Single User, 4 Transmitters

## ❖ Delay versus Load ratio

✓ LAA ED: -70 dB





# CDF Results: Single User, 8 Transmitters

## ❖ Percentage of time occupation

✓ Load ratio of 0.8

- Average percentage of time occupation

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-65	0.7695	0.9903	0.3557	0.0922	0.1135	0.2080	0.2925	0.1855	0.1770	0.3353
-70	0.9203	1.0265	0.2915	0.1587	0.1790	0.2911	0.2864	0.1947	0.1775	0.3679
-75	1.1362	0.7790	0.4017	0.1704	0.2443	0.3199	0.2603	0.0831	0.0826	0.3530

- “Average” percentage of time occupation (excluding bad locations)

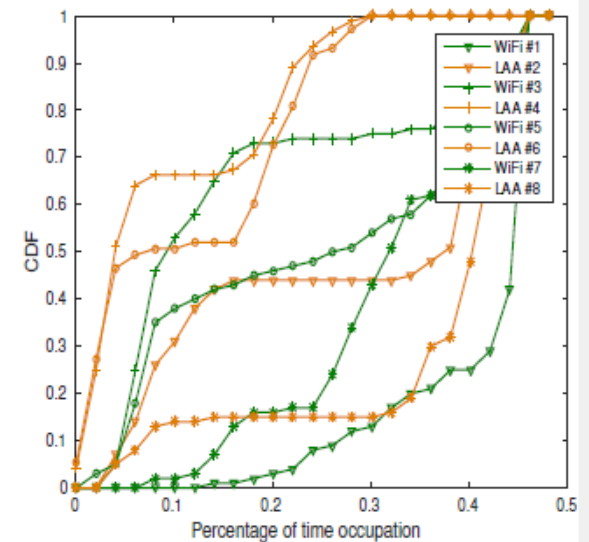
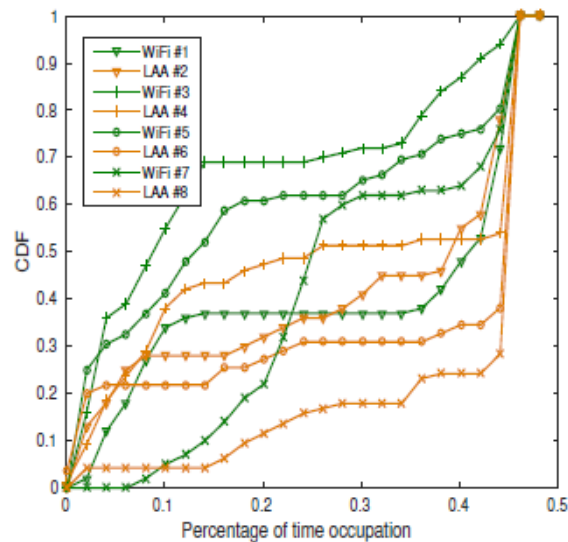
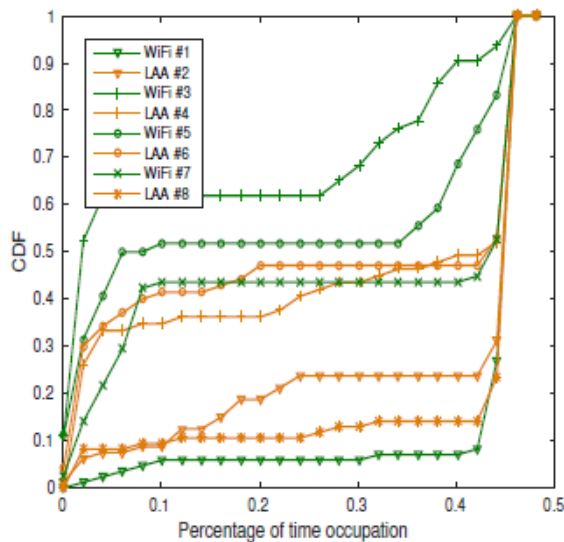
LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-65	0.8978	1.4595	0.4175	0.0789	0.1438	0.2575	0.3933	0.3412	0.3212	0.4038
-70	0.8949	1.2632	0.3104	0.1381	0.1561	0.2903	0.2653	0.2827	0.3156	0.3997
-75	1.1201	0.8264	0.4061	0.1491	0.2590	0.3060	0.2741	0.0953	0.1099	0.3471

# CDF Results: Single User, 8 Transmitters

## ❖ Percentage of time occupation

✓ Load ratio of 0.8

- CDF



Wifi's curves is "moving right" → better performance.

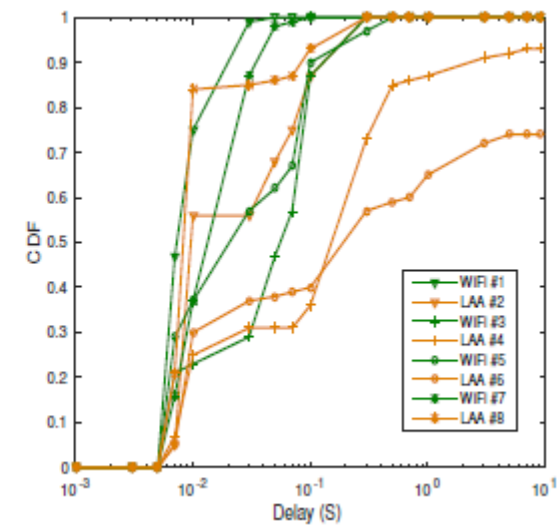
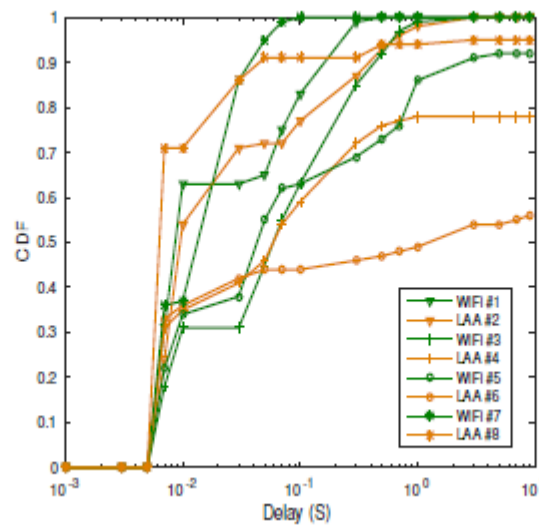
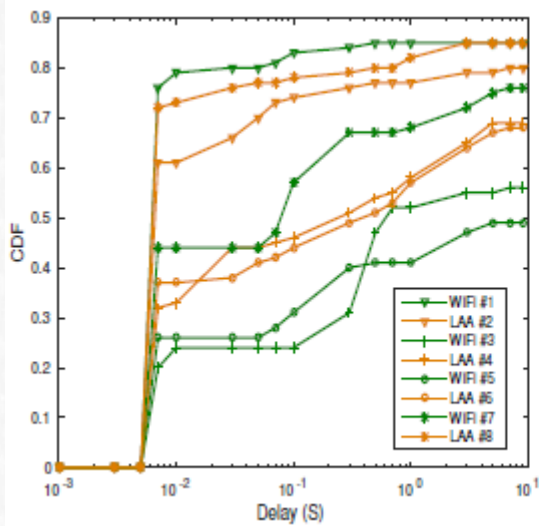
# CDF Results: Single User, 8 Transmitters

## ❖ Delay with Definition II

- ✓ Load ratio of 0.8
  - “Average” delay (excluding bad locations)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-65	1.3573	0.1544	0.0111	4.2830	1.0795	0.0554	0.0324	0.2335	0.2949	0.0568
-70	0.1574	0.3732	0.0451	0.2188	0.3436	0.0223	0.1168	0.7433	0.5943	0.0385
-75	0.0331	0.5160	0.0091	0.0622	0.0437	0.0176	0.0391	0.8400	1.1591	0.0257

## • CDF



Wfi's curves is “moving left” → better performance.

# CDF Results: Single User, 8 Transmitters

## ❖ Percentage of time occupation

✓ Load ratio of 0.5

- Average percentage of time occupation

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-65	0.6826	0.7197	0.2719	0.1521	0.1067	0.1519	0.2188	0.1229	0.1362	0.2418
-70	0.9338	0.7805	0.2805	0.1893	0.1835	0.2804	0.2194	0.1791	0.1462	0.2358
-75	1.0905	0.7495	0.3215	0.2186	0.2328	0.3176	0.2503	0.1128	0.0892	0.2971

- “Average” percentage of time occupation (excluding bad locations)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-65	0.8638	1.0874	0.2981	0.1997	0.1486	0.2175	0.2777	0.2584	0.2365	0.3148
-70	0.9245	0.9323	0.2910	0.1777	0.1686	0.2873	0.2151	0.2171	0.2142	0.2859
-75	1.0905	0.7495	0.3215	0.2186	0.2328	0.3176	0.2503	0.1128	0.0892	0.2971

- “Average” delay (excluding bad locations)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-65	0.2215	0.2050	0.0074	0.0246	0.7179	0.1362	0.0173	0.1788	0.6128	0.0109
-70	0.0319	0.0891	0.0126	0.0447	0.0611	0.0092	0.0409	0.0774	0.1985	0.0398
-75	0.0122	0.0597	0.0054	0.0171	0.0195	0.0065	0.0148	0.0703	0.1439	0.0100

The delay is a bit strange, should we exclude bad locations?

# CDF Results: Single User, 8 Transmitters, Different Thresholds

## ❖ Percentage of time occupation

✓ Load ratio of 0.8

- Average percentage of time occupation

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-70,-65,-65,-70	0.7891	0.9444	0.3234	0.1303	0.1399	0.1955	0.2806	0.1857	0.1616	0.3165
-75,-65,-65,-75	0.7494	0.7705	0.3021	0.1501	0.0892	0.2080	0.1962	0.2057	0.1645	0.2041
-75,-70,-70,-75	0.9786	0.9026	0.3028	0.1626	0.2144	0.2988	0.2377	0.2382	0.1339	0.2928
-65,-70,-70,-65	0.9218	1.0109	0.3346	0.1432	0.1602	0.2838	0.2868	0.2018	0.1867	0.3356
-65,-75,-75,-65	1.2553	0.7446	0.4244	0.1662	0.2765	0.3881	0.2811	0.0503	0.0453	0.3679

- “Average” percentage of time occupation (excluding bad locations)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-70,-65,-65,-70	0.9609	1.3438	0.3226	0.1579	0.1937	0.2866	0.2745	0.3710	0.3427	0.3556
-75,-65,-65,-75	0.9203	1.0265	0.2915	0.1587	0.1790	0.2911	0.2864	0.1947	0.1775	0.3679
-75,-70,-70,-75	0.9389	1.1072	0.3079	0.1437	0.1802	0.3071	0.2355	0.3013	0.2274	0.3429
-65,-70,-70,-65	0.8994	1.2729	0.3392	0.1331	0.1636	0.2635	0.3336	0.2435	0.3048	0.3910
-65,-75,-75,-65	1.2741	0.8457	0.4228	0.2107	0.2565	0.3842	0.3375	0.0589	0.0595	0.3899

# CDF Results: Single User, 8 Transmitters, Different Thresholds

## ❖ Percentage of time occupation

✓ Load ratio of 0.5

- Average percentage of time occupation

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-70,-65,-65,-70	0.6630	0.7570	0.2131	0.1820	0.1108	0.1571	0.2408	0.1334	0.1334	0.2494
-75,-65,-65,-75	0.6435	0.6797	0.2332	0.1576	0.0968	0.1560	0.1907	0.1504	0.1445	0.1940
-75,-70,-70,-75	0.9224	0.8216	0.2609	0.1787	0.1886	0.2942	0.2406	0.1746	0.1547	0.2516

- “Average” percentage of time occupation (excluding bad locations)

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-70,-65,-65,-70	0.8963	1.1151	0.2573	0.2058	0.1736	0.2597	0.3038	0.2458	0.2697	0.2958
-75,-65,-65,-75	0.7820	1.0014	0.2589	0.1776	0.1379	0.2076	0.2377	0.2675	0.2436	0.2526
-75,-70,-70,-75	0.9381	0.9162	0.2772	0.1818	0.1817	0.2974	0.2453	0.1866	0.2102	0.2741

[-75,-70,-70,-75] is the best combination so far.

# CDF Results: Single User, 8 Transmitters, Adaptive

## ❖ Procedure

- ✓ Each eNB has an initial value of ED,  $E_{dmin} = -62$  dBm,  $E_{dmax} = -82$  dBm
- ✓ In average, there are  $k$  packets arrived during time interval  $T$ , if the increasing number of packets in the buffer is larger than  $k \cdot R$ ,  $ED = ED + 1$ ; if the number of packets in the buffer is decreasing,  $ED = ED - 1$ ;

## ❖ Percentage of time occupation

- ✓ Load ratio of 0.8
  - Average percentage of time occupation

ED, Ratio	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-62, 0.3	0.8517	0.6208	0.3607	0.1287	0.1101	0.2162	0.2229	0.0916	0.0889	0.2175
-72, 0.3	1.1004	0.8926	0.3270	0.1909	0.2332	0.3492	0.2706	0.1570	0.0930	0.3721
-82, 0.3	1.1750	0.7918	0.3876	0.2205	0.2550	0.3119	0.2765	0.0945	0.0918	0.3291
-72, 0.2	1.0967	0.8584	0.3450	0.1820	0.2273	0.3424	0.2700	0.1586	0.0912	0.3387
-72, 0.4	1.1003	0.8506	0.3417	0.1635	0.2541	0.3411	0.2555	0.1637	0.0729	0.3584

Performance depends on the adopted parameters.

# CDF Results: Multiple Users

## ❖ Simulation setting

- ✓ Each AP/eNB have five users
- ✓ 802.11ac/LTE theoretical throughput and minimum SNR requirement (20 MHz, normal CP) (AC: MCS 0~11, LTE: MCS 0~14)

Modulation type	Coding Rate	AC SNR	LTE SNR	AC throughput	LTE throughput
QPSK	1/2	5	2.0	14.4	16.8
QPSK	3/4	9	5.5	21.7	25.2
16-QAM	1/2	11	7.9	28.9	33.6
16-QAM	3/4	15	12.2	43.3	50.4
64-QAM	2/3	18	15.3	57.8	67.2
64-QAM	3/4	20	17.5	65	75.6

- ✓ WiFi: MU-MIMO
- ✓ CW is updated if NACK is received from any user



# CDF Results: Multiple Users

❖ Percentage of time occupation, 8 transmitters

✓ Load ratio of 0.8

LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-65	35.79	26.77	42.26	33.26	32.11	35.54	27.36	25.16	23.58	30.97
-70	38.79	27.56	42.63	35.73	35.78	41.02	28.34	24.87	26.05	30.99
-75	38.88	24.83	42.18	32.54	38.61	42.20	25.44	21.47	19.74	32.67
-75, -70, -70, -75	39.29	28.32	42.99	37.05	36.54	40.59	26.51	28.03	27.36	31.36

✓ Load ratio of 0.5

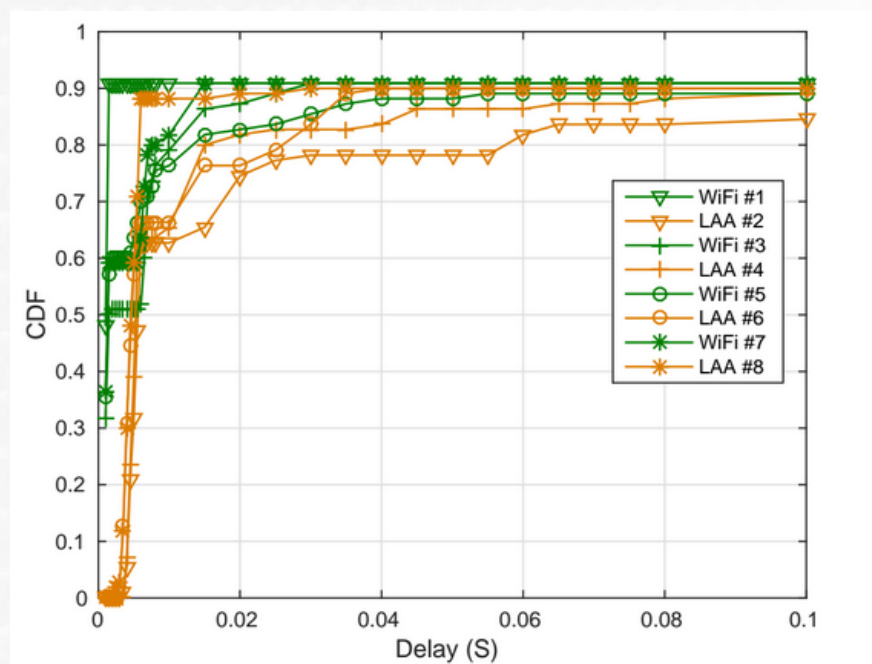
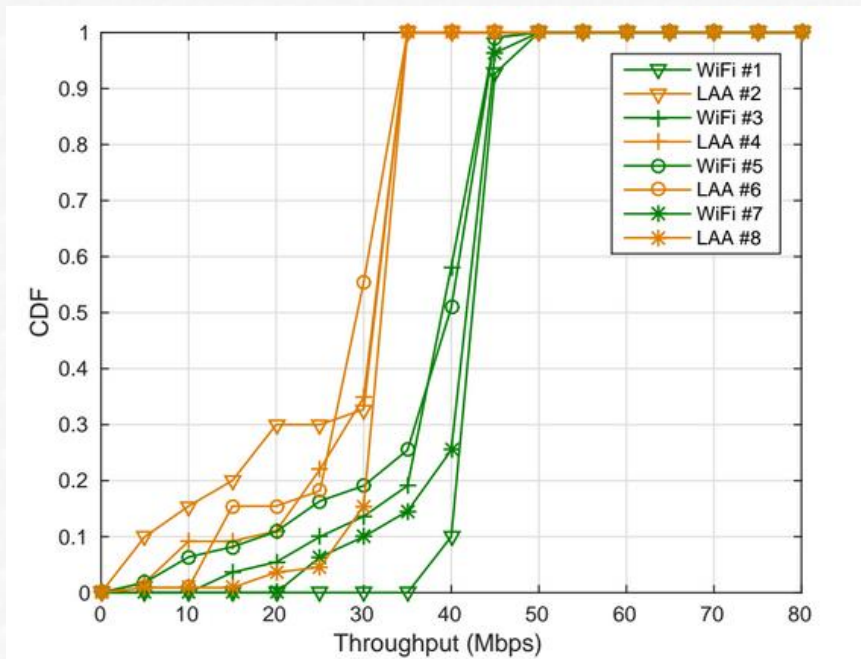
LAA threshold (dBm)	WiFi	LAA	WiFi (#1)	WiFi (#3)	WiFi (#5)	WiFi (#7)	LAA (#2)	LAA (#4)	LAA (#6)	LAA (#8)
-65	25.50	24.94	28.48	23.92	24.08	25.74	25.10	24.82	25.07	24.78
-70	26.88	22.05	26.41	26.52	25.81	28.77	23.41	20.47	20.42	23.90
-75	27.78	21.85	28.40	26.90	27.14	28.70	21.72	20.47	21.07	24.12
-75, -70, -70, -75	27.94	22.60	28.46	27.48	27.18	28.64	21.84	22.31	22.09	24.15

Choosing different thresholds for LAA can also improve the performance.

# CDF Results: Multiple Users

❖ CDF for LAAED = [-75,-70,-70,-75]

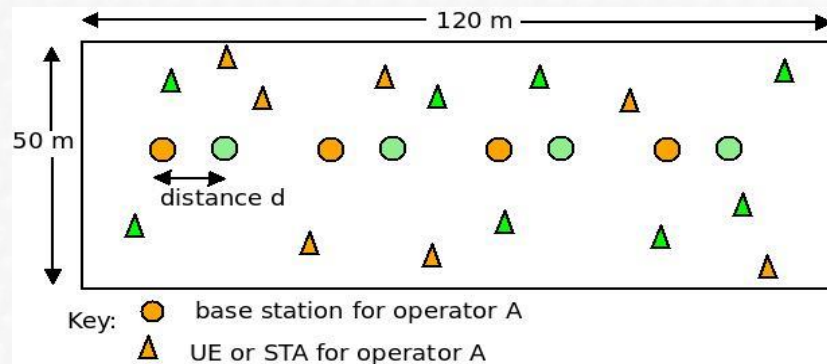
✓ Load ratio of 0.8



# Simulation Results from NS-3

## ❖ Simulation setting [1]

### ✓ Layout

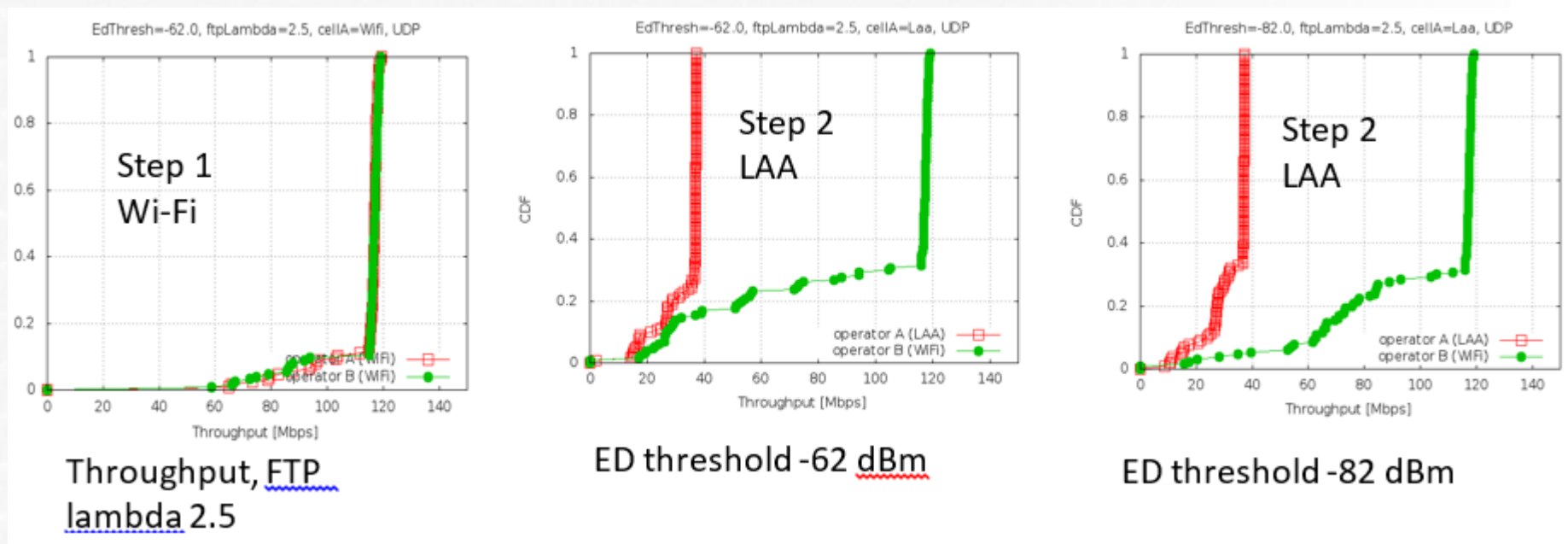


- ✓ Traffic model: FTP Model 1 over UDP/TCP,  $\lambda = 0.5/1.5/2.5$
- ✓ WiFi: 1) 802.11n 2\*2 MIMO, channel 36 (20 MHz); 2) a standard DCF for best effort traffic; 3) CCAED = -62 dBm, CCACS = -88 dBm; 4) No beamforming
- ✓ LAA: 1)  $C_{wmin} = 15$ ,  $C_{wmax} = 1023$ ; 2) maximum TxOP length (configured from 4 msec to 20 msec); 3) implement reservation signals to occupy the channel until the first subframe with data; 4) CCAED = -62/-72/-82 dBm
- ✓ UEs (STAs) move around at 3 km/h, no re-dropping.

# Simulation Results from NS-3

## ❖ Simulation Results [1]

✓ Throughput,  $\lambda = 2.5$

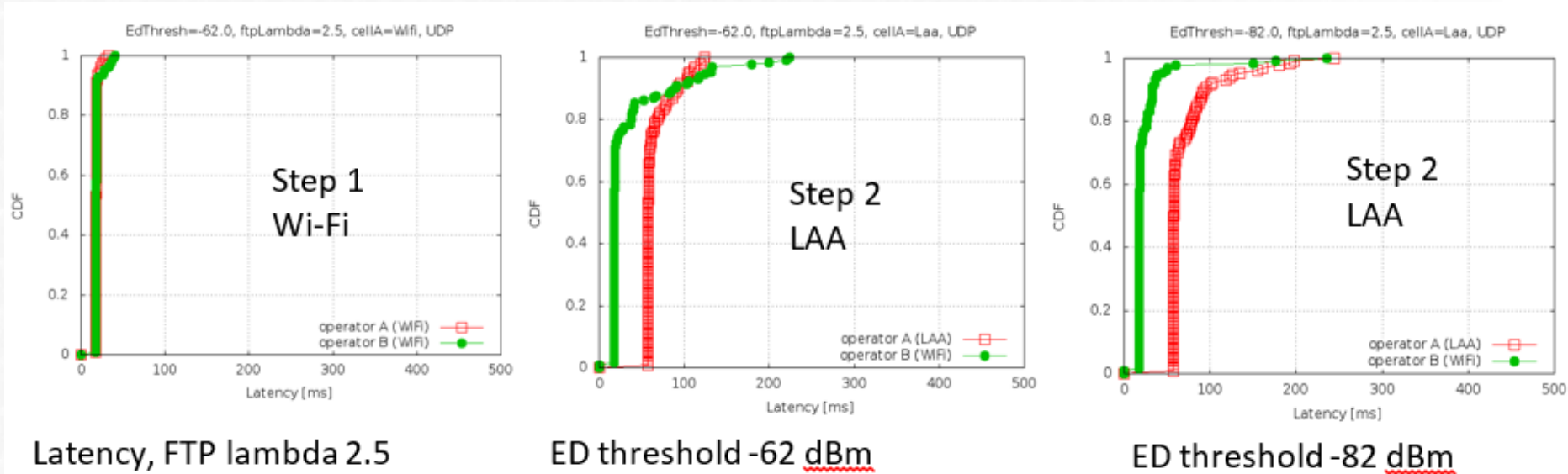


LAA is becoming worse. The probability of low throughput increases.

# Simulation Results from NS-3

## ❖ Simulation Results [1]

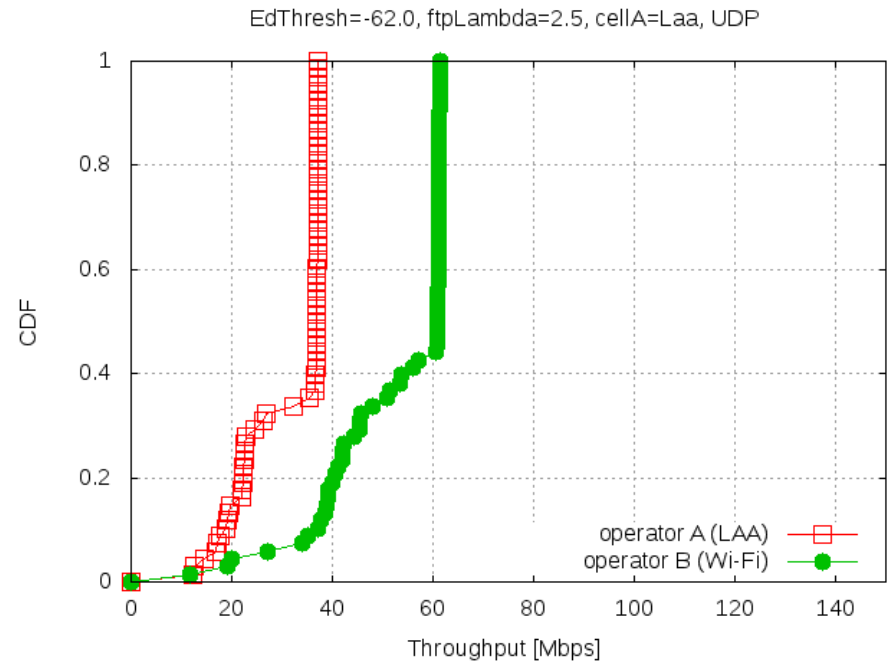
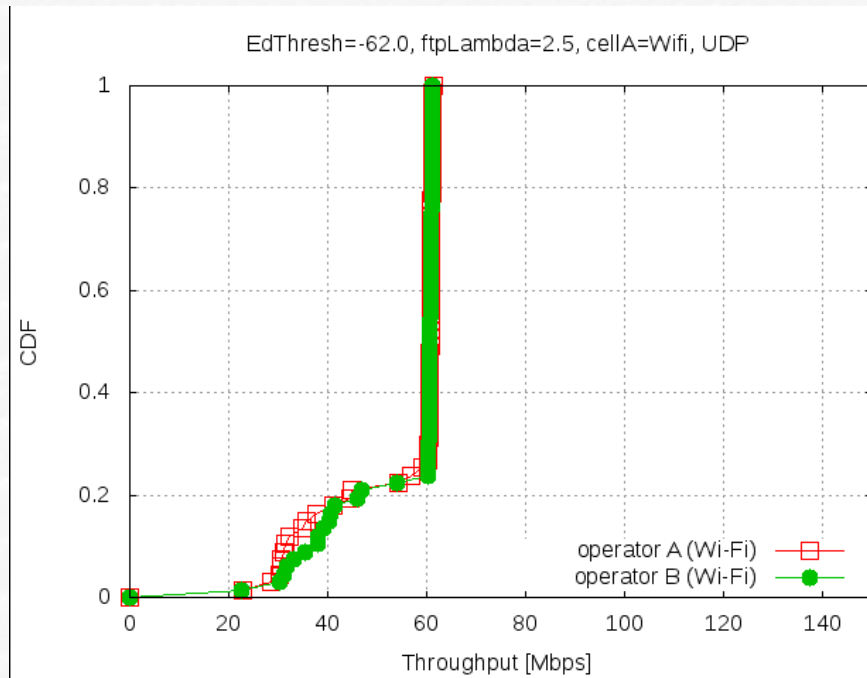
✓ Latency, lambda = 2.5



# Simulation Results from NS-3

## ❖ Simulation Results, 802.11n SISO

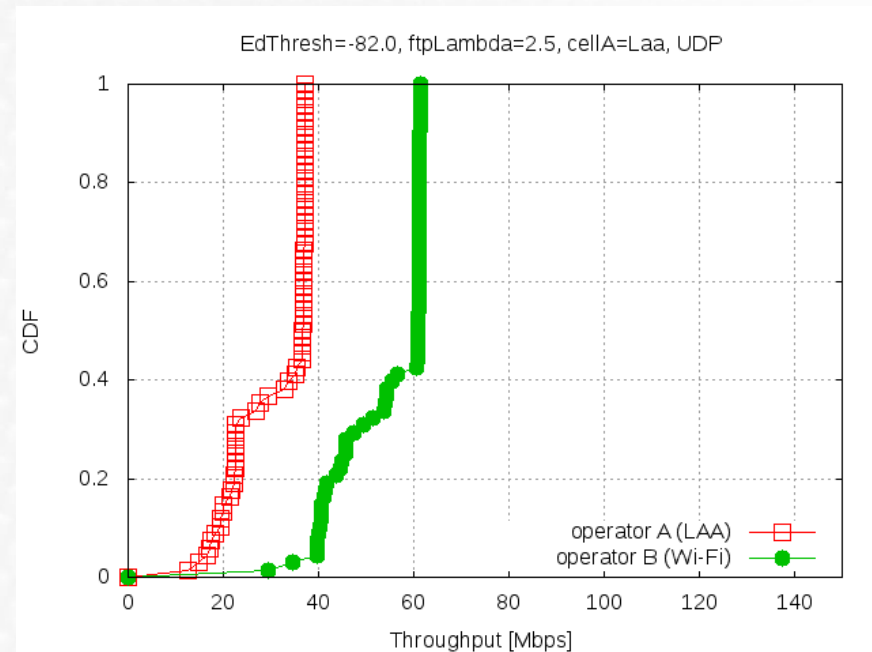
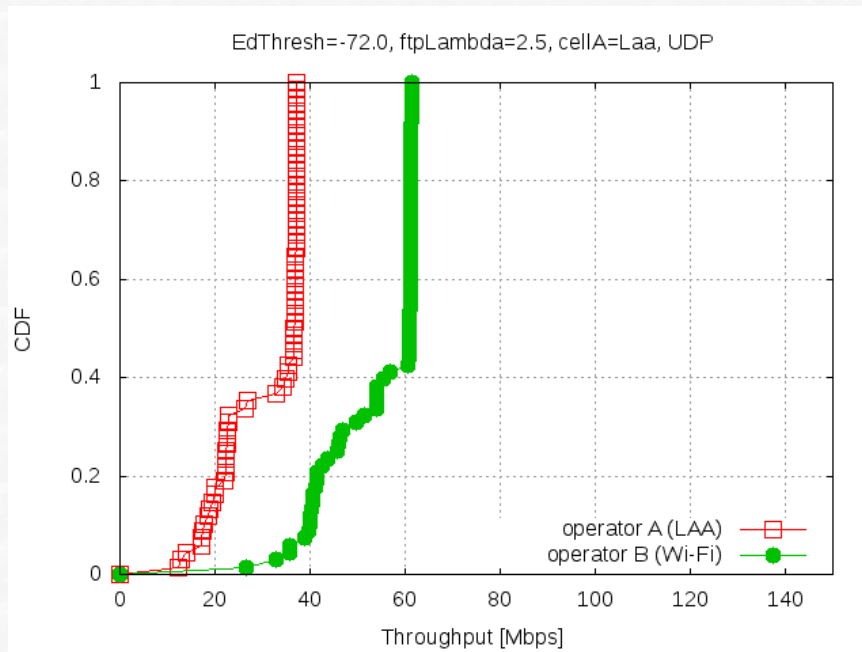
✓ Throughput, lambda = 2.5 (WiFi/-62 dBm)



# Simulation Results from NS-3

## ❖ Simulation Results, 802.11n SISO

✓ Throughput, lambda = 2.5 (-72 dBm/-82 dBm)

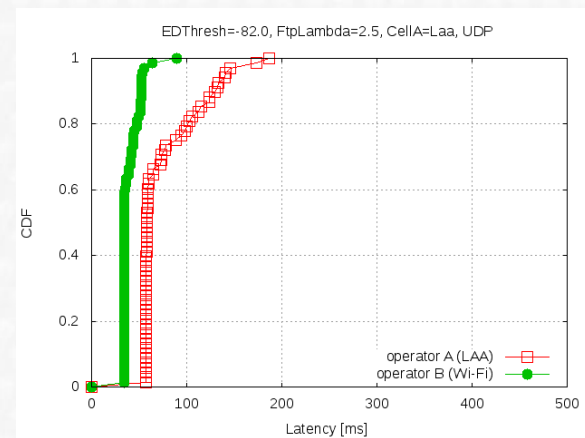
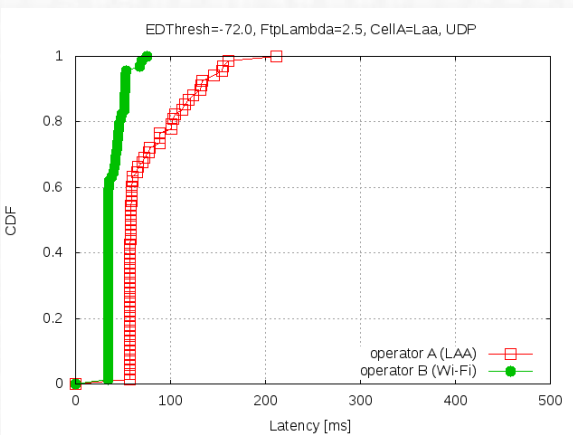
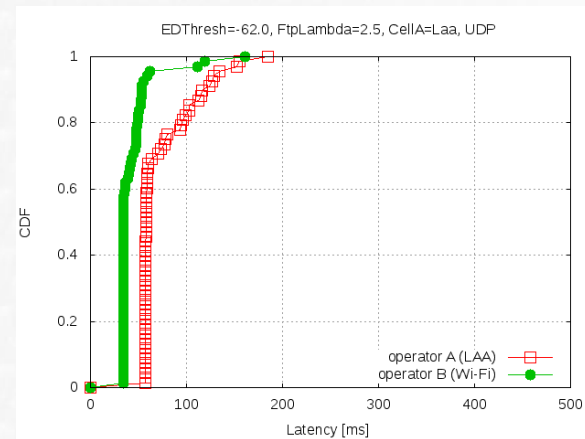
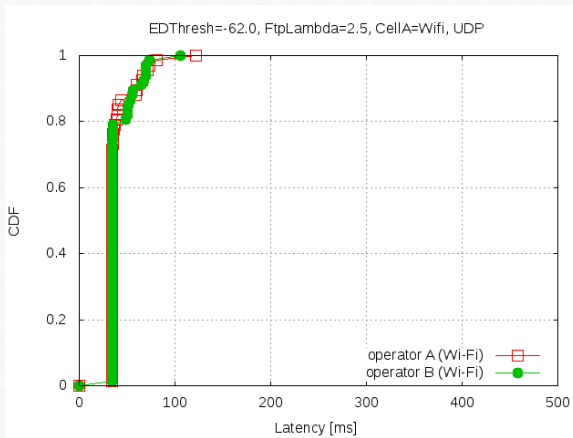


The difference is not large.

# Simulation Results from NS-3

## ❖ Simulation Results, 802.11n SISO

✓ Latency, lambda = 2.5 (WiFi/-62/-72/-82 dBm)





# Next steps

- ❖ Continue to think about some adaptive algorithms for LAA ED
- ❖ Consider multiple subchannels