# Performance anomaly in 802.11 Wi-Fi networks

## Motivation

In 802.11n Wi-Fi networks, the physical layer data rate for each Station (STA) is dynamically selected based on the Modulation and Coding Scheme (MCS) which is itself determined by the received signal quality. The signal quality can degrade due to factors such as path loss, fading, or interference, leading to the selection of a lower MCS index and, consequently, a reduced data rate for STAs that are far from the AP. On the other hand, STAs that are in close proximity to the Access Point (AP) experience high signal quality, and thus higher MCS and higher data rates.

This leads to a differentiated network environment where certain STAs may operate at elevated data rates (for instance, 72.2 Mbps) while others, constrained by poor signal conditions, are limited to lower data rates (for example, 7.2 Mbps). This rate disparity in a Wi-Fi network environment raises an important question: how does the presence of a slow STA affect the throughput of faster STAs and the aggregate throughput of the network?

## Objective

The objective is to quantitatively evaluate the impact of a slow STA on the throughput of faster STAs within an 802.11n network environment. The analysis will focus on determining the aggregate network throughput and the average STA throughput when the network comprises of multiple fast STAs and at least one slow STA.

## The IEEE 802.11n PHY Rates Table

We begin with an understanding of the 802.11n PHY rates. The term "MCS" stands for modulation and coding scheme. The MCS defines the numbers of useful bits which can be carried by one symbol. In Wi-Fi IEEE 802.11n standard, the MCS depends on the received signal strength (RSS). The higher the signal strength the higher the MCS and more useful bits can be transmitted in a symbol. Thus, the PHY bit rate depends on the MCS chosen. IEEE 802.11n devices can transmit at speeds of 7.2, 14.4. 21.7, 28.9, 43.3, 57.8, 65 and 72.2 Mbps as shown in the table below.

| MCS Index | Rx Sensitivity (dBm) | Modulation Technique | Coding Rate | Guard Interval (ns) | PHY Rate |
|---|---|---|---|---|---|
| 0 | -82 | BPSK | 1/2 | 400 | 7.2 Mbps |
| 1 | -79 | QPSK | 1/2 | 400 | 14.4 Mbps |
| 2 | -77 | QPSK | 3/4 | 400 | 21.7 Mbps |
| 3 | -74 | 16 QAM | 1/2 | 400 | 28.9 Mbps |
| 4 | -70 | 16 QAM | 3/4 | 400 | 43.3 Mbps |
| 5 | -66 | 64 QAM | 2/3 | 400 | 57.8 Mbps |
| 6 | -65 | 64 QAM | 3/4 | 400 | 65 Mbps |
| 7 | -64 | 64 QAM | 5/6 | 400 | 72.2 Mbps |

Table 1: 802.11n bit rates for different modulation schemes, and the minimum received signal power for achieving each bit rate. NSS = 1, and the guard Interval is 400ns.

In the above table, Rx Sensitivity is the minimum RSS. A simulation assumption in NetSim is that the transmitter knows the RSS at the receiver. Thus, the transmitter chooses the MCS by comparing the RSS against the Receiver-Sensitivity for different MCSs. The highest possible MCS is then chosen.

## Calculating distances at which the PHY rate changes

In this section, we compute the AP-STA distance thresholds for the different PHY rates. We know that

$$\mathrm{P_r} = P_t - c_0 - 10\,\eta \log_{10}(d)$$

At 2.4 GHz, $c_0$ is 40.09 $dB$. For $P_t = 100\,mW\ (20\,dBm),\ \eta = 3$, and setting $P_r$ as equal to the receive sensitivity (Ref: Table 1), and we get the following inequality for the 7.2 Mbps PHY rate.

$$-82 \leq 20 - 40.09 - 30 \times log(d) < -79$$

This gives 91.95$m$ < $d$ ≤ 115.76 $m$. Similarly, we compute the AP-PHY distance for all the rates and arrive at the table below.

| Rx Sensitivity (dBm) | Data Rate (Mbps) | $d_{max}\ (m)$ | $d_{min}\ (m)$ |
|---|---|---|---|
| **-82** | 7.2 | 115.76 | 91.96 |
| **-79** | 14.4 | 91.95 | 78.88 |
| **-77** | 21.7 | 78.87 | 62.66 |
| **-74** | 28.9 | 62.65 | 46.1 |
| **-70** | 43.3 | 46.09 | 33.91 |
| **-66** | 57.8 | 33.9 | 31.41 |
| **-65** | 65 | 31.4 | 29.09 |
| **-64** | 72.2 | 29.08 | 1.0 |

Table 2: We see the maximum and minimum AP-STA distances for different 801.11g PHY bit rates. The PHY rate is 0 for $\boldsymbol{d}$ ≥ 115.76$\boldsymbol{m}$. We have chosen $P_t = 100\ mW$ and $\eta = 3$.

Table 2 can be visualized as shown below.

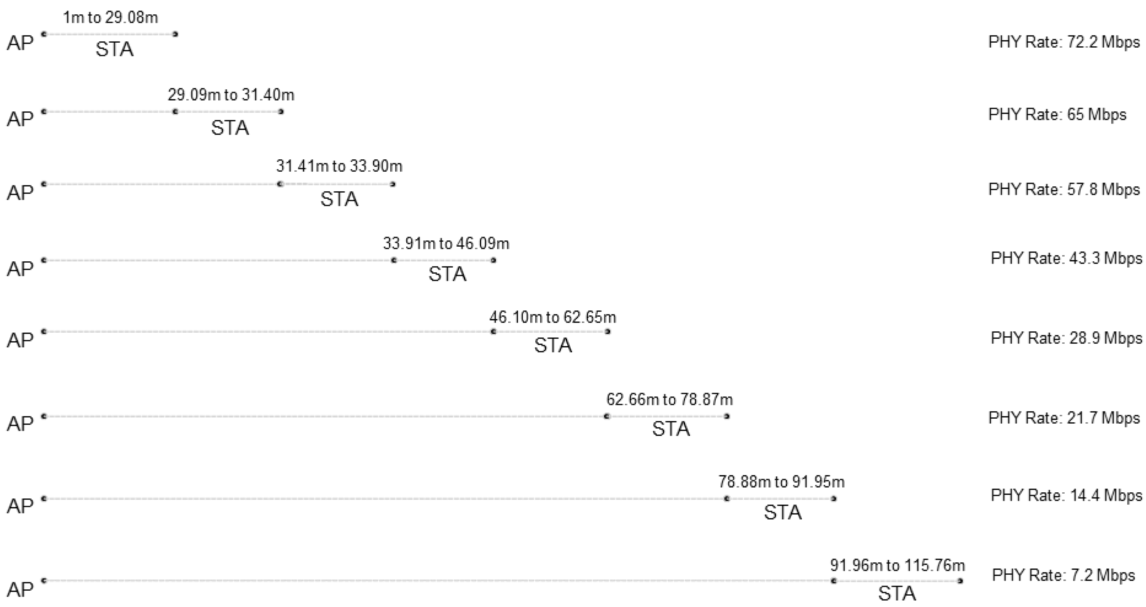



Table 3: Illustration of variation in AP data (PHY) rate vs. distance for $\boldsymbol{P_t = 100\ mW}$ and $\boldsymbol{\eta = 3.5}$

# Case 1: 1AP-1STA, throughput variation with distance

## Network Setup

Open NetSim and click on **Your Work> 1AP-1STA, throughput variation with distance >** Open MCS-7-Distance-5m Sample.

NetSim UI displays the configuration file corresponding to this experiment as shown below in Figure 1.

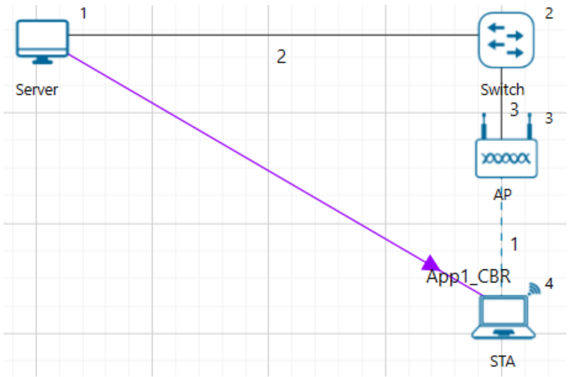



Figure 1: Network set up for studying the Impact of distance on Wi-Fi Throughput for 1AP-1STA scenario.

## Procedure

The following set of procedures were done to generate this sample.

**Step 1:** Click on Internetworks on the home screen. Once you enter set the grid length to 150m × 150m.

**Step 2:** A network scenario is created in NetSim GUI comprising of 1 Wired Node, 1 L2 Switch, 1 Access Point and 1 Wireless Node. The wired node is named Server, the wireless node is named STA, and the access point is named AP.

**Step 3:** The position of the Wireless Node and the Access Point in the grid environment is set according to the values given in Table 4.

| Device Positions | | |
|---|---|---|
| | **STA** | **AP** |
| **X** | 100 | 25 |
| **Y** | 100 | 30 |

Table 4: Device Positions

**Step 4:** In AP and STA, the Interface 1 (Wireless) > Physical Layer, Protocol Standard is set to IEEE802.11n. Then in Interface 1 (Wireless) > Datalink Layer check that the Medium Access Protocol is set to DCF.

**Step 5:** Right-click the link ID (of a wired/wireless link) and select Properties to access the link's properties. The parameters are set according to the values given in the below in Table 5 and Table 6.

| Wireless Link Properties | |
|---|---|
| Channel | Path Loss Only |
| Path Loss Model | Log Distance |
| Path Loss Exponent | 3 |

Table 5: Wireless Link Properties

| Wired Link Properties | |
|---|---|
| Max Uplink Speed (Mbps) | 100 |
| Max Downlink Speed (Mbps) | 100 |
| Uplink BER | 0 |
| Downlink BER | 0 |
| Uplink Propagation Delay (µs) | 0 |
| Downlink Propagation Delay (µs) | 0 |

Table 6: Wired Link properties

**Step 6:** Configure applications between any nodes by selecting an application from the Set Traffic tab. Right click on App1 CBR and select the following properties. Source: Server with Node ID 1, Destination: STA with Node ID 4, Packet Size: 1460 Bytes and Inter Arrival Time: 467.2 µs. These packet size and inter packet arrival time settings results in traffic generation rate that equals 25 Mbps. The Transport Protocol is set to UDP.

**Step 7:** Under Configure Reports > Logs enable the 802.11 Radio Measurements. Then Run simulation for 10 sec.

**Step 8:** Note down the following output metrics: (i) Application Throughput from the Results Window, and (ii) Received power (at the STA) from the Radio Measurements

**Step 9:** We need to repeat the experiment for different STA-AP distance. Re-open the saved scenario and change the distance between AP and STA by changing the Y co-ordinate of the STA as 55, 57, 65, 80, 95, 110 and 135, while retaining the X co-ordinate as-is. This corresponds to cases in which AP-STA distance is 30, 32, 40, 55, 70, 85, 110 and 116 respectively. In all these cases note down the Application Throughput and Receiver Sensitivity as explained in Step 8.

## Results

Simulation results with PHY rates and application throughputs are tabulated in Table 7.

| 802.11n PHY rate and Application Throughput Comparison | | | | | |
|---|---|---|---|---|---|
| $d_{min} - d_{max}$ (m) | Distance(m) (AP – STA) | Received Power (dBm) | Receiver Sensitivity (dBm) | PHY Rate (Mbps) | Application Throughput (Mbps) |
| 0 – 29.08 | 5 | -41.06 | -64 | 72.2 | 23.99 |
| 29.09 – 31.40 | 30 | -64.40 | -65 | 65 | 23.11 |
| 31.41 – 33.90 | 32 | -65.24 | -66 | 57.8 | 22.08 |
| 33.91 – 46.09 | 40 | -68.15 | -70 | 43.3 | 19.47 |
| 46.10 – 62.65 | 55 | -72.30 | -74 | 28.9 | 15.77 |
| 62.66 – 78.87 | 70 | -75.44 | -77 | 21.7 | 13.25 |
| 78.88 – 91.95 | 85 | -77.97 | -79 | 14.4 | 10.00 |
| 91.96 – 115.76 | 110 | -81.33 | -82 | 7.2 | 5.79 |
| Beyond 115.76 | 116 | 0 | 0 | 0 | 0 |

Table 7: We see how PHY rate and Application Throughput varies with AP-STA distance, with the log distance pathloss mode where the pathloss exponent ($\eta$) is set to 3.0

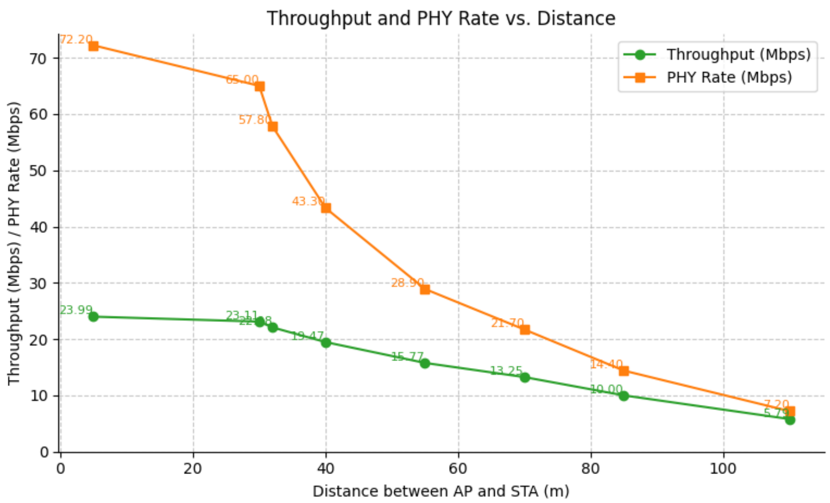



Figure 2: A plot of Application throughput and PHY Rate vs AP-STA distance for Wi-Fi working per IEEE 802.11n. The log-distance pathloss model was used with the pathloss exponent $\eta$ set to 3.

## Remarks on Application throughput and nominal PHY rate

We make two important observations from Figure 2.

1. The throughput at the application layer in 802.11 WLANs is markedly lower than the nominal PHY layer data rate. The 802.11 frame structure includes various control frames (like RTS, CTS, ACK though RTS/CTS is not enabled in this example) and frame headers that do not contribute to the application layer data but are essential for the operation of the MAC protocol. This overhead reduces the amount of bandwidth available for actual application data. Additionally, the CSMA/CA mechanism that is part of the 802.11 protocol introduces a random backoff period following each transmission attempt. This backoff strategy is essential for reducing collision probability in a shared medium but concurrently imposes a penalty on channel efficiency.
2. The gap between application throughput and PHY rate is higher at higher PHY rates due to the fixed-size and fixed-rate nature of control frames and headers. These overheads, when transmitted at lower rates, take up more relative time as PHY rates increase, thus disproportionately reducing effective throughput for higher-speed transmissions.

## Case 2: Comparison of Wi-Fi performance of All-fast STAs vs. One-slow-remaining-fast STAs

## Network Setup: All-fast STAs

Open NetSim and click on **Your Work> Comparison of Wi-Fi performance of All-fast STAs vs. One slow-remaining-fast STAs > All-fast STAs>** Open 1AP-2STA Sample

NetSim UI displays the configuration file corresponding to this experiment as shown below.

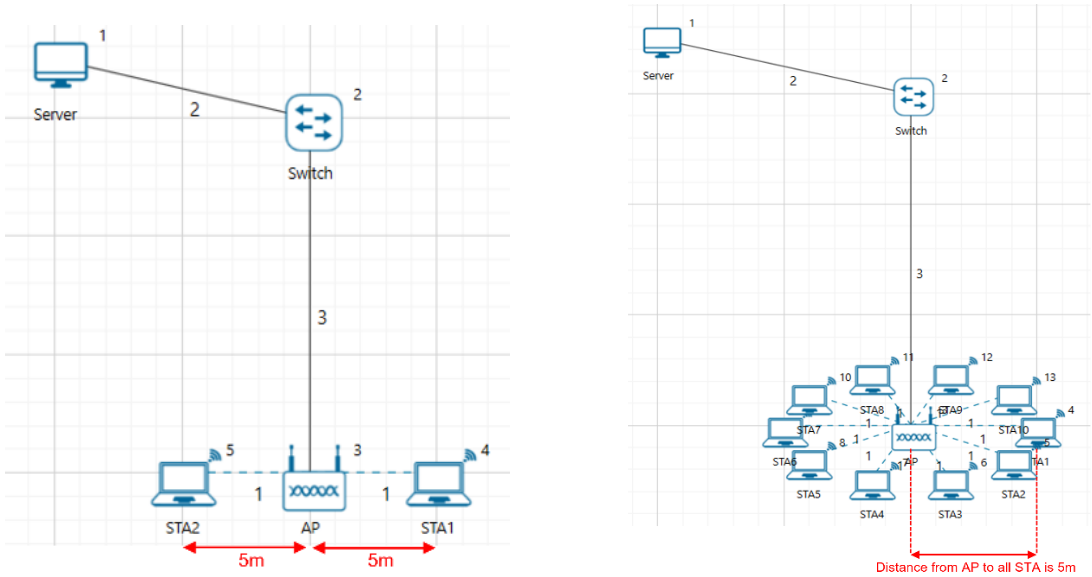



Figure 3: Left: Network set up for studying the Impact of distance on Wi-Fi Throughput for STA at Max MCS, Distance from AP to STA1 and STA2 is 5m and MCS is 7. Both STAs are generating saturation uplink traffic. Right: Network set up for studying the Impact of distance on Wi-Fi Throughput for STA at Max MCS, Distance from AP to all STA is 5m and MCS is 7. All STAs are generating saturation uplink traffic.

## Procedure

The following set of procedures were done to generate this sample.

**Step 1:** Click on Internetworks on the home screen. Once you enter set the grid length to 135m × 70m.

**Step 2:** A network scenario is created in NetSim GUI comprising of 1 Wired Node, 1 L2 Switch, 1 Access Point and 1 Wireless Node. The wired node is named Server, the wireless node is named STA, and the access point is named AP.

**Step 3:** In AP and STA, the Interface 1 (Wireless) > Physical Layer, Protocol Standard is set to IEEE802.11n. Then in Interface 1 (Wireless) > Datalink Layer check that the Medium Access Protocol is set to DCF.

**Step 4:** Right-click the link ID (of a wired/wireless link) and select Properties to access the link's properties. The parameters are set according to the values given in the below in Table 8 and Table 9.

| Wireless Link Properties | |
|---|---|
| Channel | Path Loss Only |
| Path Loss Model | Log Distance |
| Path Loss Exponent | 3 |

Table 8: Wireless Link Properties

| Wired Link Properties | |
|---|---|
| Max Uplink Speed (Mbps) | 100 |
| Max Downlink Speed (Mbps) | 100 |
| Uplink BER | 0 |
| Downlink BER | 0 |
| Uplink Propagation Delay (µs) | 0 |
| Downlink Propagation Delay (µs) | 0 |

Table 9: Wired Link properties

**Step 5:** Configure applications between any nodes by selecting an application from the Set Traffic tab. Right click on App1 CBR and select the following properties. Source: Server with Node ID 1, Destination: STA with Node ID 4 and 5, Packet Size: 1460 Bytes and Inter Arrival Time: 467.2 µs. These packet size and inter packet arrival time settings results in traffic generation rate that equals 25 Mbps. The Transport Protocol is set to UDP.

**Step 7:** Run simulation for 10 sec.

**Step 8:** Note down the following output metrics: (i) Application Throughputs from the Results Window.

**Step 9:** Similarly increase the number of STAs 1, 3, 4, 5, 6, 7, 8, 9, 10 and log the cumulative and average throughput.

## Network Setup: One-slow-remaining-fast STAs

Open NetSim and click on **Your Work> Comparison of Wi-Fi performance of All-fast STAs vs. One slow-remaining-fast STAs > One-slow-remaining-fast STAs >** Open 1AP-2STA Sample

NetSim UI displays the configuration file corresponding to this experiment as shown below.

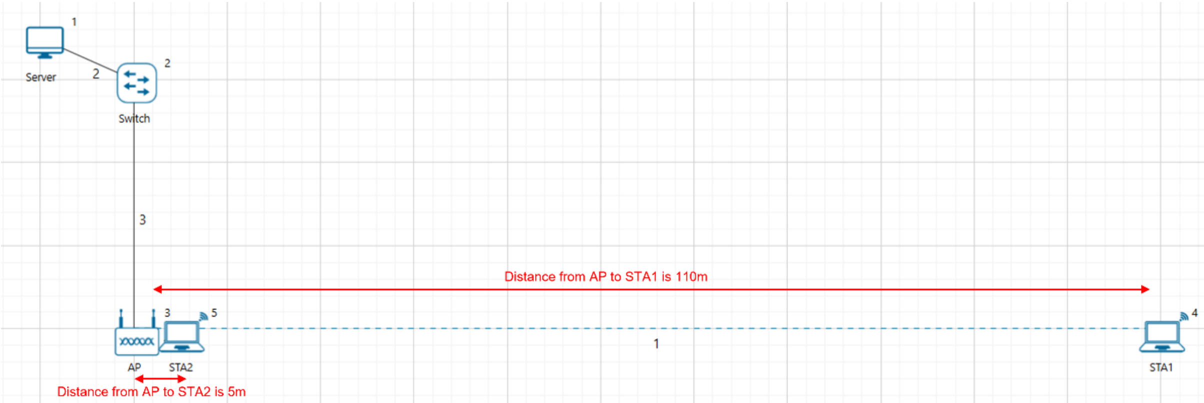



Figure 4: Network set up for studying the Impact of distance on Wi-Fi Throughput for 1 slow STA, Distance from AP to STA1 is 110m and MCS is 0 (slow STA), Distance from AP to other STA is 5m and MCS is 7. Both STAs are generating saturation uplink traffic.

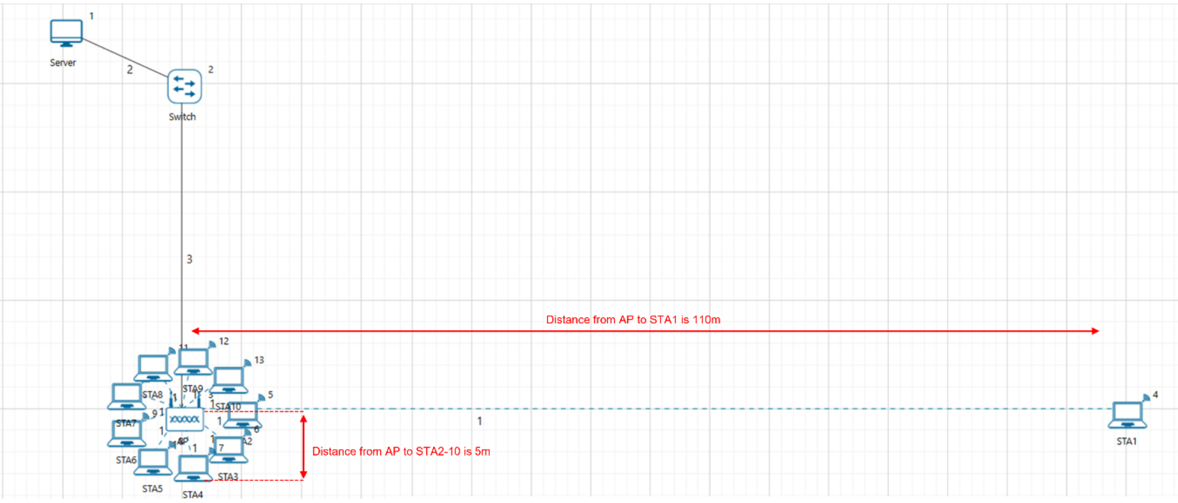



Figure 5: Network set up of 1AP-10STA scenario for studying the Impact of distance on Wi-Fi Throughput for 1 slow STA, Distance from AP to STA1 is 110m and MCS is 0 (slow STA), Distance from AP to other STA is 5m and MCS is 7. All STAs are generating saturation uplink traffic.

## Procedure

The following set of procedures were done to generate this sample.

**Step 1:** Click on Internetworks on the home screen. Once you enter set the grid length to 70m × 70m.

**Step 2:** A network scenario is created in NetSim GUI comprising of 1 Wired Node, 1 L2 Switch, 1 Access Point and 1 Wireless Node. The wired node is named Server, the wireless node is named STA, and the access point is named AP.

**Step 3:** In AP and STA, the Interface 1 (Wireless) > Physical Layer, Protocol Standard is set to IEEE802.11n. Then in Interface 1 (Wireless) > Datalink Layer check that the Medium Access Protocol is set to DCF.

**Step 4:** Right-click the link ID (of a wired/wireless link) and select Properties to access the link's properties. The parameters are set according to the values given in the below in Table 10 and Table 11.

| Wireless Link Properties | |
|---|---|
| Channel | Path Loss Only |
| Path Loss Model | Log Distance |

| Path Loss Exponent | 3 |
|---|---|

Table 10: Wireless Link Properties

| Wired Link Properties | |
|---|---|
| Max Uplink Speed (Mbps) | 100 |
| Max Downlink Speed (Mbps) | 100 |
| Uplink BER | 0 |
| Downlink BER | 0 |
| Uplink Propagation Delay (µs) | 0 |
| Downlink Propagation Delay (µs) | 0 |

Table 11: Wired Link properties

**Step 5:** Configure applications between any nodes by selecting an application from the Set Traffic tab. Right click on App1 CBR and select the following properties. Source: Server with Node ID 1, Destination: STA with Node ID 4 and 5, Packet Size: 1460 Bytes and Inter Arrival Time: 467.2 µs. These packet size and inter packet arrival time settings result in traffic generation rate that equals 25 Mbps. The Transport Protocol is set to UDP.

**Step 7:** Run simulation for 10 sec.

**Step 8:** Note down the following output metrics: (i) Application Throughputs from the Results Window.

**Step 9:** Similarly increase the number of STAs 1, 3, 4, 5, 6, 7, 8, 9, 10 and log the cumulative and average throughput.

## Results

| | All STAs at 72.2 Mbps PHY rate | | One STA at 7.2 Mbps PHY rate, and all the remaining STAs at 72.2 Mbps PHY rate | |
|---|---|---|---|---|
| Number of STAs | Cumulative Throughput (Mbps) | Average Throughput (Mbps) | Cumulative Throughput (Mbps) | Average Throughput (Mbps) |
| 1 | 23.97 | 23.97 | 5.78 | 5.78 |
| 2 | 25.06 | 12.53 | 9.94 | 4.97 |
| 3 | 25.38 | 8.46 | 11.68 | 3.89 |
| 4 | 25.33 | 6.33 | 13.19 | 3.30 |
| 5 | 25.19 | 5.04 | 13.86 | 2.77 |
| 6 | 24.92 | 4.15 | 14.78 | 2.46 |
| 7 | 24.79 | 3.54 | 15.94 | 2.28 |
| 8 | 24.52 | 3.07 | 16.17 | 2.02 |
| 9 | 24.37 | 2.71 | 17.01 | 1.89 |
| 10 | 24.15 | 2.42 | 16.81 | 1.68 |

Table 12: Results of all STAs at high MCS, Cumulative throughput and Average Throughput of all STAs.

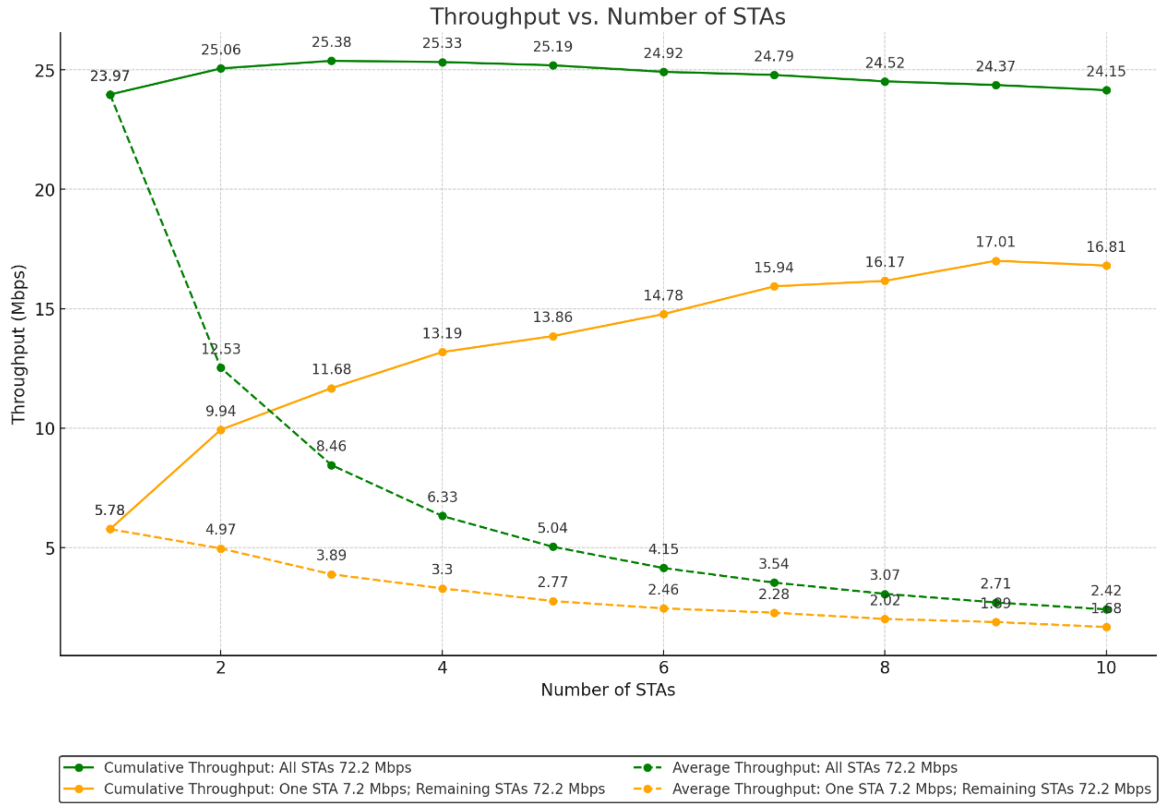



Figure 6: The graph presents a comparison of cumulative and average throughputs across a range of station (STA) counts for two scenarios within a wireless network: one where all STAs are operating at a PHY rate of 72.2 Mbps, and another where one STA operates at a reduced PHY rate of 7.2 Mbps with the remaining STAs at 72.2 Mbps.

# Discussion

The plot in Figure 6 offers a contemporary comparison to Figure 4 in [1], with the difference that our plot pertains to the 802.11n standard as opposed to the legacy 802.11b standard referenced in the paper.

From Figure 6 we see that the network with all high-rate STAs (72.2 Mbps) maintains a higher cumulative and average throughput compared to the mixed-rate scenario. This shows that the presence of even a single lower-rate STA can disproportionately affect the overall network performance due to the slower transmission rates consuming more airtime. The average throughput per STA, indicated by the dashed lines, decreases as the number of STAs increases, which is typical in shared medium networks due to increased contention. We observe that the fast hosts see their throughput decrease roughly to the order of magnitude of the slow host's throughput. Let us understand why.

The Distributed Coordination Function (DCF) is a fundamental media access control (MAC) technique used in IEEE 802.11 wireless networks to facilitate multiple access by arbitrating the transmission rights of various stations contending for a shared wireless medium. It employs a carrier sense multiple access with collision avoidance (CSMA/CA) mechanism, alongside a random backoff algorithm, to regulate access and minimize collisions. Under DCF, each station has a statistically equal probability of accessing the medium, which ostensibly leads to a fair distribution of transmission opportunities among all contending stations. However, the protocol does not account for the variance in time required by different stations to transmit an identical volume of data, particularly when these stations operate at heterogeneous data rates. Stations with lower data rates consume more airtime for a given data payload compared to their higher data rate counterparts. Consequently, the disproportionate airtime consumption by slower stations reduces the available airtime for all other stations, leading to a suboptimal utilization of the shared medium. In our example a slow host transmitting at 7.2 Mb/s to capture the channel 10 times longer than hosts transmitting at 72.2 Mb/s. This results in an overall degradation of network throughput, disproportionately affecting the performance of stations capable of higher data rates.

We see that although the presence of a slow host decreases the throughput perceived by the other ones, its impact on the cumulative throughput decreases when the number of hosts increases. This is due to the fact that the slow host uses a diminishing proportion of the channel as the number of hosts rises.

In [1], the authors derive an approximate expression for a throughput is as follows:

$$X_f = X_s = \frac{S_d}{(N-1) \cdot T_f + T_s + P_c(N) \cdot t_{jam} \cdot N}$$

Where $X_f$is throughput at the MAC layer of each of the $N-1$, fast hosts, $X_s$ is throughput at the MAC layer of slow host. $N$ is number of nodes, and $T_f$ and $T_s$ is transmission time for fast nodes and slow nodes for a packet, respectively. $P_c(N)$ is probability of collision, is $S_d$ frame size and $t_{jam}$is the delayed time experienced by collision. A more precise expression for throughput is presented in section VI(A) of [2]. The authors provide a generalization of the well-known Bianchi analysis, introduce a fixed-point formalization from which they analytically estimate the impact of the smallest transmission rate on overall network throughput. Their results align with the performance anomalies discussed in the current document.

While the evolution from 802.11b to 802.11n brought enhancements at both PHY and MAC layers, it did not resolve the performance anomaly issue. This study demonstrates that even recent wireless standards are prone to unequal airtime usage. Additional research is required to devise methods to mitigate the detrimental impact of lower-speed devices on the overall throughput efficiency of Wi-Fi networks operating under the 802.11 standards.

## References

[1] Martin Heusse, Gilles Berger-Sabbatel, Franck Rousseau and Andrzej Duda, "Performance Anomaly of 802.11b," *presented at the IEEE INFOCOM 2003, San Francisco, CA, 2003,* July 2003.

[2] A. Kumar, E. Altman, D. Miorandi, and M. Goyal, "New Insights From a Fixed-Point Analysis of Single Cell IEEE 802.11 WLANs," *IEEE/ACM Transactions on Networking,* Jun 2007.

[3] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun., vol. 18, no. 3, pp. 535–547,* Mar. 2000.

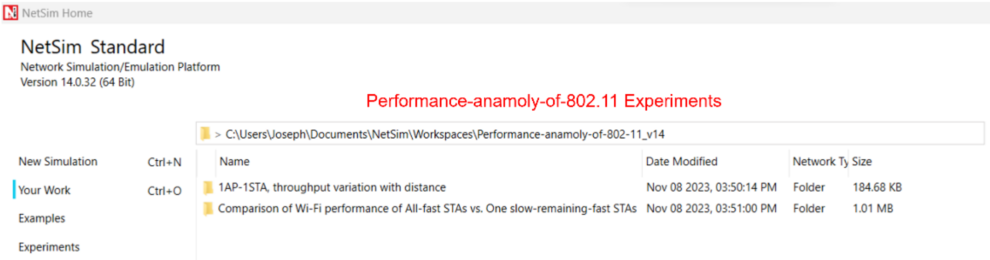
## Appendix: Download URL

The configuration files (scenario, settings, and other related files) of the examples discussed in this analysis are available for users to import and run in NetSim.

Users can download the files from NetSim's git-repository.
Link: https://github.com/NetSim-TETCOS/Performance-anamoly-of-802_11_v14/archive/refs/heads/main.zip

1. Click on the link given and download the folder.
2. Extract the zip folder. The extracted project folder consists of one NetSim Experiments file, namely *Performance-anamoly-of-802-11_v14.netsimexp*
3. Import per steps given in section 4.9.2 in NetSim User Manual
4. All the experiments can now be seen folder wise within NetSim > Your Work. It will look like the image shown below.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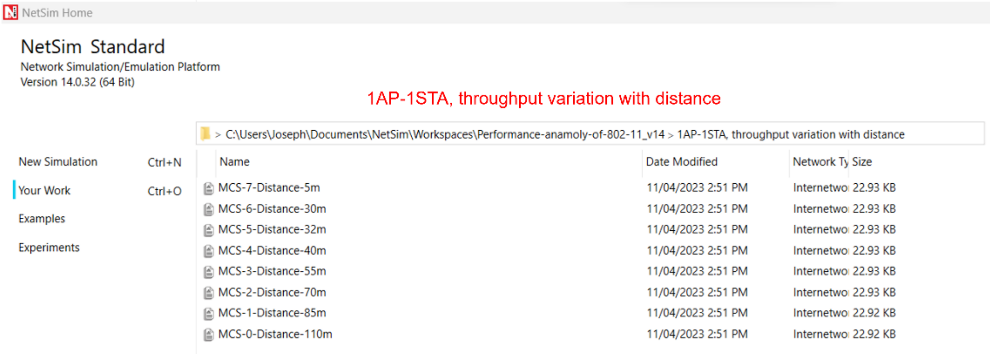
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MCS-3-Distance-55m 11/04/2023 2:51 PM Internetwo 22.93 KB
MCS-2-Distance-70m 11/04/2023 2:51 PM Internetwo 22.93 KB
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