Final Report for Projekt M.Sc.Informationstechnik
Comparison of Various Rate Control Algorithms at Different Distances

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1 Motivation

Wireless local area networks (WLANs) are increasingly becoming popular and ubiquitous. The performance of WLANs heavily relies on devices' ability to adapt to changing channel and network conditions. A common misconception is that increasing the data transmission speed at the transmitter leads to improved performance at the receiver. However, in certain conditions, reducing the data transmission speed can actually enhance receiver performance. This highlights the significance of rate control algorithms in Wi-Fi systems. In this project, we focus on evaluating the performance of Constant rate, Idealwifimanager, Minstrel-Ht and Thompson sampling rate control algorithms in IEEE 802.11ac-based WLANs. Through a designed simulation where the distance between the transmitter and receiver increases in each interval, we conduct a detailed examination of the throughput and packet loss of each of these rate control algorithms at various distances. Ultimately, we compare these four rate controls to each other to draw conclusions about their effectiveness and efficiency in WLAN environments.

2 Introduction

2.1 The IEEE 802.11ac standard

IEEE 802.11ac, also known as Wi-Fi 5, is an updated version of IEEE 802.11n. The defining characteristics of IEEE802.11ac encompass significantly elevated transmission rates, with theoretical capabilities extending to 6.77 gigabits per second. Furthermore, IEEE 802.11ac employs Multi-User MIMO technology, enabling routers to connect to multiple devices simultaneously. In addition to these features, IEEE 802.11ac also supports Multiple Spatial Streams, allowing multiple data streams to be transmitted simultaneously between the transmitter and receiver. This further enhances data throughput and network performance, particularly in environments with high user density or demanding applications.

IEEE 802.11ac operates exclusively in the 5 GHz frequency band. This band provides wider channels and less congestion compared to the 2.4 GHz band used by 802.11n[4].

IEEE 802.11ac utilizes higher-order modulation schemes like 256-Quadrature Amplitude Modulation.This allows for packing more data bits into each symbol transmitted, increasing the data density and contributing to the higher throughput[8].

2.2 Modulation and Coding Scheme

The utilization of higher-order modulation schemes like 256-Quadrature Amplitude Modulation (QAM) is indeed associated with the Modulation and Coding Scheme (MCS) in IEEE 802.11ac.MCS defines the modulation and coding schemes used to transmit data over the wireless channel[7].

Coding

Coding involves adding redundant information to the transmitted data to enable error detection and correction at the receiver side. Different coding rates (e.g., stronger or weaker) can be applied, offering a trade-off between: Error correction capability: Stronger coding adds more redundancy, improving the ability to detect and correct errors. Data overhead: Stronger coding also increases the amount of data transmitted, potentially reducing the effective data rate.

Modulation

Modulation is the process of converting bits into signals suitable for transmission over a physical medium, such as radio waves in Wi-Fi communication. Various modulation schemes provide different levels of data density, determining how many bits can be encoded in each symbol, and their susceptibility to errors. Wi-Fi commonly employs the following modulation techniques: Quadrature Amplitude Modulation (QAM): QAM schemes, including higher-order ones like 64-QAM and 256-QAM, enable the packing of more bits into a symbol, resulting in higher data rates. However, they are also more prone to noise and interference.

As mentioned earlier, we are utilizing the 802.11ac standard in this project, which supports 10 MCSs (MCS 0 to 9). Generally, lower MCSs prioritize reliable communications in challenging conditions, while higher-order MCSs offer the potential for significantly faster data rates in favorable channel conditions.

2.3 Rate control

As mentioned, 802.11ac offers higher data rates compared to its previous generations, which can lead to two significant challenges.Supporting higher data rate selections may require more effort to choose the optimal rate, and the difference between optimal and suboptimal rates can be substantial, severely impacting throughput [3]. Therefore, rate selection becomes of paramount importance.Rate control involves selecting transmission rates for data packets based on various factors such as channel conditions, interference, and network congestion. The primary objectives of rate control include maximizing throughput, minimizing packet loss and delay, ensuring fairness in resource allocation, adapting to changing network conditions, and optimizing energy efficiency.

2.4 Analyzing rate control algorithms

Rate control algorithms consist of two main parts [10]:

Channel quality metric

a metric that measures the link channel quality; common metrics include throughput, Frame Loss Ratio , and Signal Noise Ratio (SNR)

Efficient rate selection algorithm for dynamic channel conditions

Algorithmic approaches capable of selecting the optimal transmission rate based on measured channel metrics vary in their objectives, ranging from maximizing throughput to minimizing frame drop rates. Moreover, these algorithms continuously update themselves to adapt to changing channel conditions.

2.5 Problems concerning rate control

Issues with rate regulation

Data or control frame conflicts, as well as fluctuations in signal-to-noise ratio (SNR), have the potential to disrupt data transfer.In 802.11 networks, SNR often undergoes changes due to factors such as node movement and signal attenuation. Such changes in SNR are typically attributed to nodes moving farther apart, resulting in what is known as route loss. Free-space path loss is a measure of power loss relative to the distance (d) between the transmitter and receiver, with (λ) representing the signal wavelength (in meters). Free-space path loss is calculated using the formula $\left(\frac{4\pi d}{\lambda}\right) \cdot 2$ Achieving optimal throughput hinges on selecting the most suitable data rate for a given path loss. However, 802.11 networks operate within the 2.4 GHz and 5 GHz bands, which are shared with other technologies like Bluetooth, microwaves, and cordless phones. This sharing of wireless spectrum can lead to media congestion and noise interference, which, in turn, can significantly degrade SNR [10].

Frame collisions

In WLANs, collisions occur when frames sent by different devices overlap in the same frequency channel, resulting in interference and reduced Signal-to-Noise Ratio (SNR). This interference can lead to increased receive errors and potential transmission failure. Although the IEEE 802.11 standard employs Carrier-Sense Multiple Access with Collision Avoidance to mitigate collisions, complete elimination is not possible due to factors like coincident backoff times and the hidden terminal problem. During unicast transmission, a transmitter considers the transmission successful upon receiving an "Acknowledge" (ACK) frame from the destination device. However, if no ACK is received, the transmitter cannot distinguish between transmission failure due to collision or weak signal strength caused by channel propagation loss. As a result, rate control algorithms often choose lower transmission rates to increase energy per bit at the receiver, which can mitigate transmission failures caused by low signal strength. However, this approach may unnecessarily reduce transmission rates in cases where collisions are the primary cause of transmission failures.[10].

Bit Error Rate

Bit Error Rate (BER) is a critical metric in digital data transmission evaluation, representing the ratio of incorrectly received bits to the total transmitted. In communication systems, data is converted into binary form, but real-world channels face challenges like noise and interference, causing bit errors. BER quantifies the likelihood of encountering these errors, computed by dividing the erroneous bits by the total transmitted. Rate control algorithms often respond to high BER by reducing data rates to enhance signal clarity and lower error rates.[2].

2.6 Classification of Rate Control Algorithms

Existing rate control algorithms can be categorized into two groups.

Open-Loop rate controls

Open-loop rate control, is a mechanism where the transmitter selects the transmission rate without receiving feedback from the receiver. This approach relies on estimating the optimal rate based on factors such as channel conditions and signal strength, without considering the actual reception outcome. While it offers simplicity and fast decision-making, it may not always lead to the most efficient use of the wireless channel as it lacks feedback from the receiver [9].

Closed-Loop rate controls

In closed-loop rate control, the transmitter selects the data rate with the assistance of receiver feedback, which typically includes additional information about channel conditions perceived by the receiver, such as the signal-to-interference-plus-noise ratio. This mechanism enables the transmitter to dynamically adjust the transmission rate in response to changing channel conditions and signal strength, optimizing throughput and reliability while minimizing errors. Despite potential overhead and complexity associated with feedback mechanisms and algorithm design, closed-loop rate control is preferred in scenarios where accurate and efficient rate adaptation is essential for achieving high-performance wireless communication [9].

2.7 UDP Protocol

In this project, we have used the UDP protocol for sending packets between the sender and receiver. This protocol is connectionless, meaning that it does not establish a direct connection between the sender and receiver before transferring data, allowing packets to be sent more quickly. Additionally, it can be more scalable and send packets with less delay. However, UDP does not have an internal mechanism for handling errors that may occur during packet transmission. Nevertheless, this simplicity and reduced overhead of UDP can contribute to faster speeds and lower network congestion.

3 Implementation

As previously mentioned, the aim of this project is to evaluate the performance of four rate control algorithms, namely Constant rate, Idealwifimanager, Minstrel-HT, and Thompson sampling, across different distances. This section examines the operation and details of each of these rate control algorithms.

3.1 Constant rate

A simple method for controlling rate in wireless communication networks, such as those that follow the IEEE 802.11ac standard, is constant rate control. With this approach, the transmission rate is manually adjusted to a predefined value and stays constant for the duration of the communication session. Constant rate control maintains a constant transmission rate regardless of changes in signal quality or interference levels, in contrast to adaptive rate control approaches that dynamically adjust transmission rates based on channel conditions or received feedback from receivers.

3.2 IdealWifiManager

The IdealWifiManager algorithm is a closed-loop rate control algorithm inspired by Receiver-Based Auto Rate algorithms. This means that both the channel quality detection mechanism and the MCS selection are handled by the receiver, which sends this information to the transmitter using Request to Send (RTS)/Clear to Send (CTS) messages. This enables the transmitter to make real-time decisions about selecting the appropriate rate based on the current channel conditions, rather than relying on the channel conditions from the previous packet. As a result, it can respond much more quickly to changes in the channel.

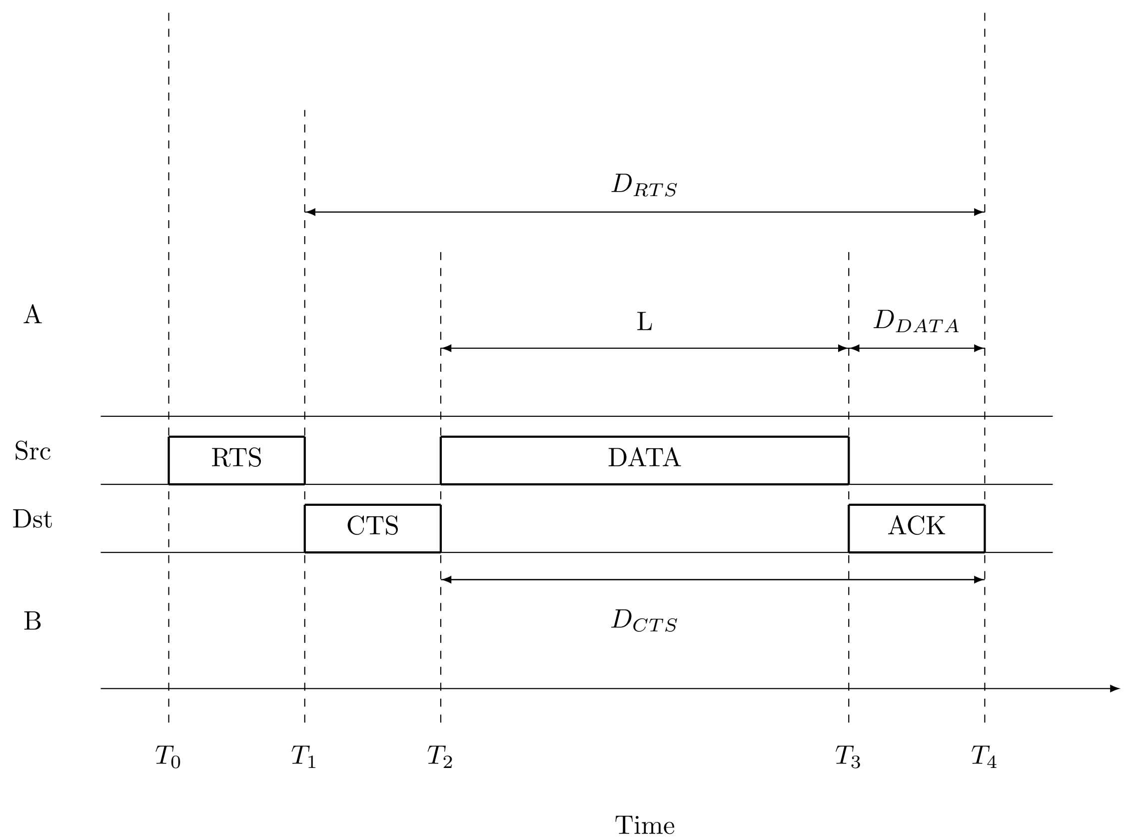

Figure 1: Time line showing the RTS/CTS protocol in the IEEE 802.11 distributed[3]

Referring to Figure 1, the transmitter Src selects a data rate and then stores the rate and packet size in the RTS. Node A, upon hearing the RTS, calculates the Requested Duration Time Slot (DRTS) using the rate and packet size carried in the RTS. This is feasible because all the necessary information for calculating DRTS for A is known. Upon receiving the RTS, the receiver Dst uses the available information about the channel conditions to make an estimate of the conditions for packet transmission. Then, Dst selects an appropriate rate based on that estimate and sends it along with the packet size in the CTS to the transmitter. Finally, Src responds to receiving the CTS by sending the data packet at the rate chosen by Dst.

However, it should be noted that since the rate is selected in a way that BER is below a predefined threshold, it can lead to overly conservative behavior in some conditions. Therefore, this algorithm may not be truly ideal in the literal sense [6],[3].

3.3 Minstrel-Ht

Minstrel-HT is an open-loop rate control algorithm that operates based on statistics obtained for different rates and calculates the actual throughput based on the success probability, packet size, and transmission time. Before sending a new frame, it selects a new sequence of rates to test, to which ten percent of frames are allocated [5]:

The rate that gives the best throughput.

The second-best throughput rate.

The rate with the highest success probability.

The lowest rate

The Minstrel-HT algorithm periodically updates a table containing four selected transmission rates every 50 milliseconds. During transmission, it utilizes this updated table to determine the rate for the majority of frames, approximately ninety percent. Essentially, it endeavors to transmit frames at the rate offering the highest throughput initially. Should transmission at this rate fail after a set number of attempts, the algorithm gracefully adjusts by attempting the next rate in the sequence. This iterative process continues until the algorithm reaches the lowest transmission rate.[1].

3.4 Thompson sampling

Thompson Sampling rate control is close loop rate control. This algorithm operates on the principles of the Thompson sampling technique, which is a Bayesian approach to solve the multi-armed bandit problem[6].

In Thompson sampling rate control, each transmission opportunity involves sampling from a Beta distribution for each possible MCS. This algorithm calculates a value for each MCS, considering the probabilistic success rate of transmitting at that MCS and the resulting physical data rate. The MCS with the highest calculated value is then selected for transmission [5].

The algorithm keeps track of the number of successes and failures for each MCS and updates these parameters upon receiving ACKs . To ensure recent feedback carries more weight, these parameters are aged over time using an exponential decay factor.

Thompson Sampling rate control focuses on optimizing MCS selection, considering factors like channel width and spatial streams. It typically chooses lower MCS for transmitting control frames.

Thompson sampling algorithm leverages feedback from the previous packet, contrasting with Idealwifimanager, which adjusts the rate based on the current packet's information.

4 Simulation

In this section, we focus on simulating an IEEE 802.11ac Wi-Fi channel, where each of the rate control algorithms is separately implemented. We utilize the ns-3 simulator for this simulation. As depicted in the figure 2, STA 1 is positioned at the origin 0, followed by the access point located ten meters away from it, and the initial position of STA 2 is twenty meters away from STA 1. It's worth noting that all devices are positioned along the x-axis coordinate. It is worth mentioning that the transmitter data rate has also been set to 150 megabytes per second. Additionally, the UDP protocol has been used for packet transmission. STA 2, representing the receiver node, moves ten meters away from the access point after each iteration, continuing this process until it reaches a distance of four hundred meters from STA 1. throughput and packet loss are measured at each iteration.

To enhance statistical accuracy, variable data is utilized for simulation, and each rate control is measured ten times under identical conditions. The simulation duration for each run is set at 100 seconds.

Following the simulation, plots illustrating the throughput and packet loss display the average values and every ten simulations. Additionally, vertical lines representing the standard deviation at each measurement point are included on the average graphs for clarity.

Furthermore, the overall standard deviation for each simulation is indicated in the chart labels. To provide better insight into the results, histograms are also employed to represent the throughput and packet loss ranges.

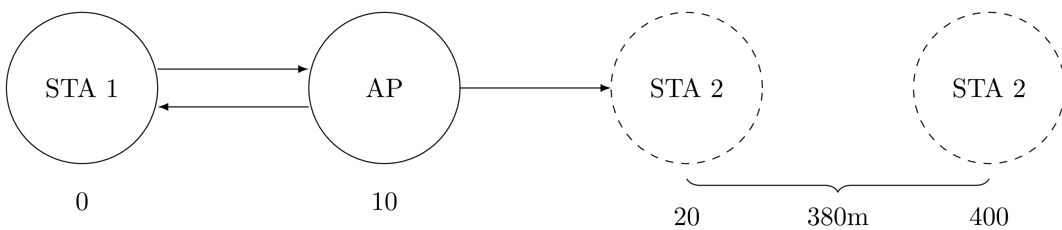

Figure 2: Simulation Topology

4.1 Constant rate

In this section, we conduct ten simulations of constant-rate with different MCSs. We start by examining the throughput. As indicated in the figure 3, each color corresponds to a specific MCS.

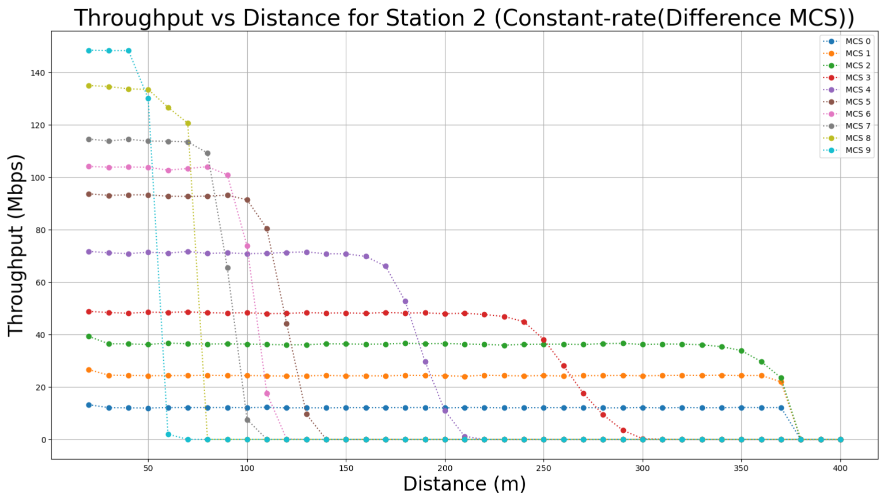

Figure 3: The throughput plot for Constant rate with Different MCSs

As observed in the throughput diagram(figure 3), each MCS provides a specific throughput during the simulation. This throughput remains relatively constant throughout the simulation until the MCS corresponds to the channel conditions, after which it gradually decreases. Initially, MCS 9 provides the highest throughput, but it decreases after 40 meters, and MCS 8 exhibits better throughput at a 50-meter interval, continuing this trend. As mentioned in the MCS section, lower-order MCSs are more resistant to channel conditions, which is clearly evident in the figure.

For instance, MCS 0 and 1, 2 receive transmitted packets up to a distance of 370 meters from the first node.

Now, if we revert to the definition of rate control, we see that optimal rate control considers the best data rate at each point. If we assume that constant rate has the capability of automatically selecting the rate, we encounter a plot like this(figure 4).

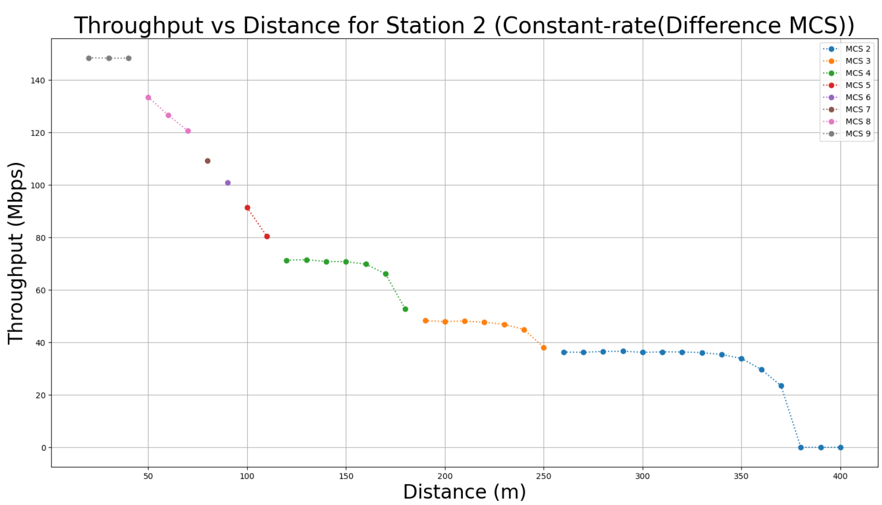

Figure 4: The best throughput plot for Constant rate algorithm at each distance

Now, we move on to the analysis of constant rate throughput histogram (figure 5).

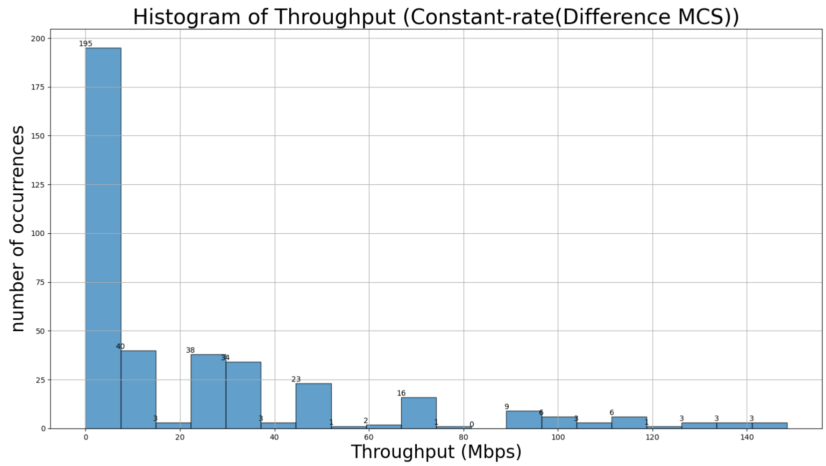

Figure 5: Histogram of throughput for Constant rate

As evident in the throughput histogram(figure 5), the values obtained fall within specific intervals. In the throughput histogram(figure 5), as the throughput decreases, the number of values obtained increases. Now, under similar conditions, we turn our attention to packet loss analysis.(figure 6)

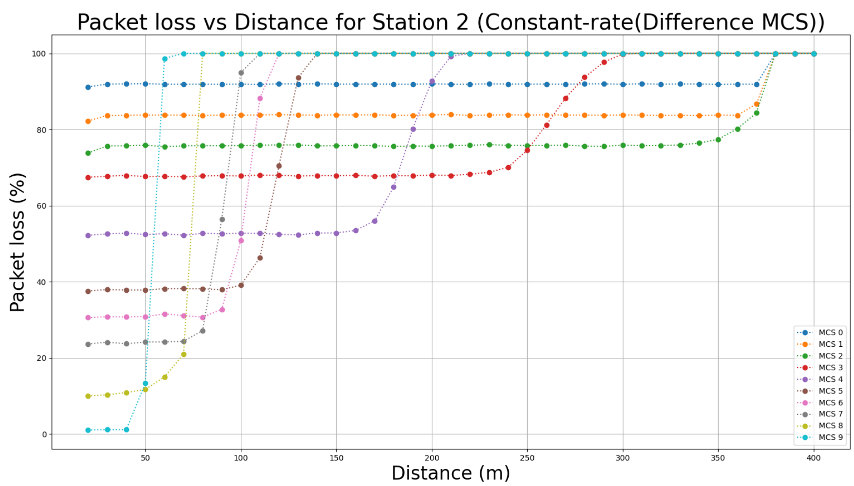

Figure 6: The packet loss plot for Constant rate with different MCSs

As observed in figure 6, up to a distance of forty meters, MCS 9 has the lowest packet loss percentage. However, this trend changes with increasing distance. An interesting point in the figure 6 is that although the packet loss percentage by lower-order MCSs 0, 1, and 2 is much higher than other MCSs throughout the experiment, they reach 100% at the furthest point compared to other MCSs. This once again underscores the resilience of these MCSs to channel conditions, including increasing distance.

Now, with a similar approach to what we had in throughput analysis, we consider the minimum percentage at each distance point.(figure 7)

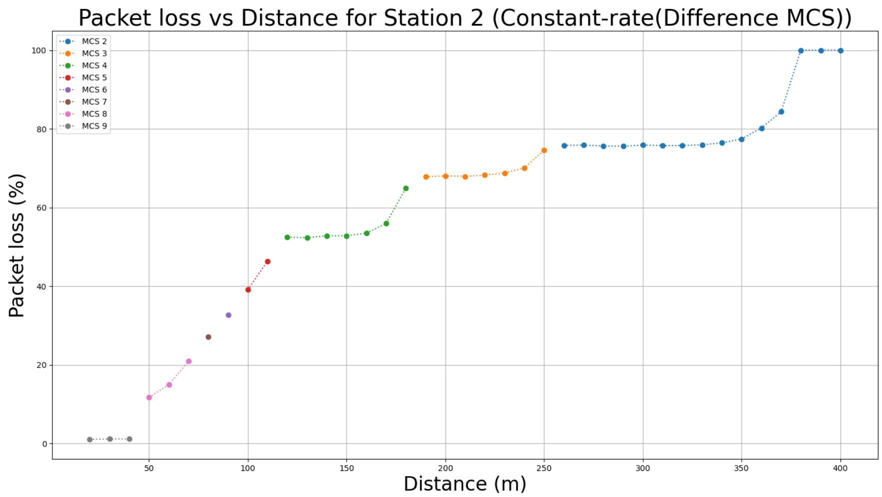

Figure 7: The lowest packet loss plot for Constant rate algorithm at each distance

And in the figure 8, the histogram of the packet loss can be observed.

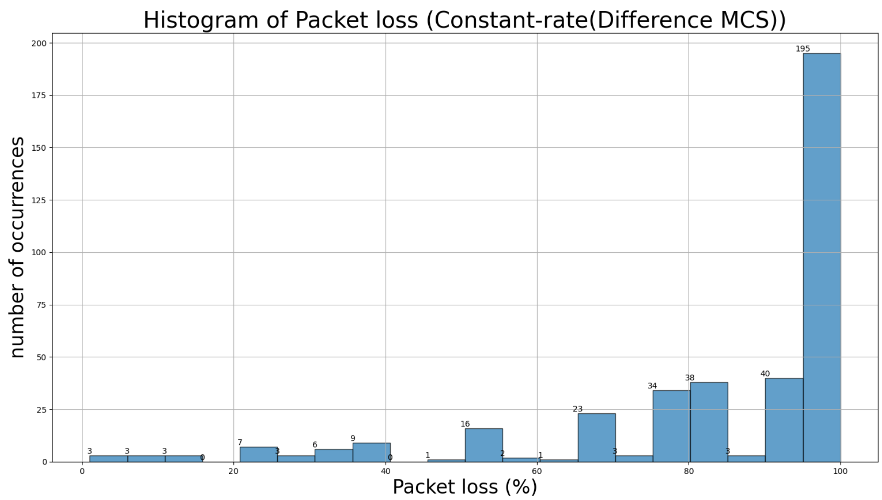

Figure 8: Histogram of packet loss for Constant rate

In the packet loss histogram(figure 8), where as the packet loss increases, the number of occurrences also increases.And this indicates that the MCSs with lower packet loss percentages have occurred less frequently.

4.2 Idealwifimanger

We begin by examining the throughput in the Idealwifimanger algorithm, as illustrated in the figure 9.

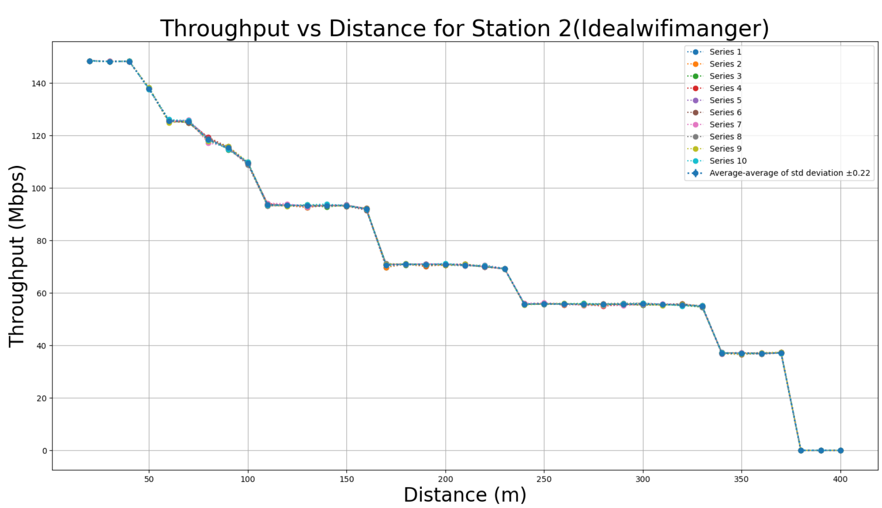

Figure 9: The throughput plot for Idealwifimanger

In the figure 9, the throughput is approximately 148.5 Mbps at distances between from 20 to 40 meters, but it decreases with increasing distance. It should be noted that the Idealwifimanager automatically adjusts the MCS according to the channel conditions and distance.In some intervals, the throughput remains relatively constant compared to the previous distance measured. For example, between distances of 110 to

160 meters, indicating that the rate control did not require a change in MCS in this range. Ultimately, the throughput drops to zero at a distance of 380 meters. As expected, the throughput exhibited a decreasing trend throughout the simulation, although it remained constant at certain intervals. Another point worth mentioning is the low standard deviation, indicating that random variables have minimal impact on the overall throughput .And this implies that despite the random variable changes, the rate control has been able to select the optimal rate for each measurement.

Now, we move on to the analysis of Idealwifimanger histogram of throughput.(figure 10)

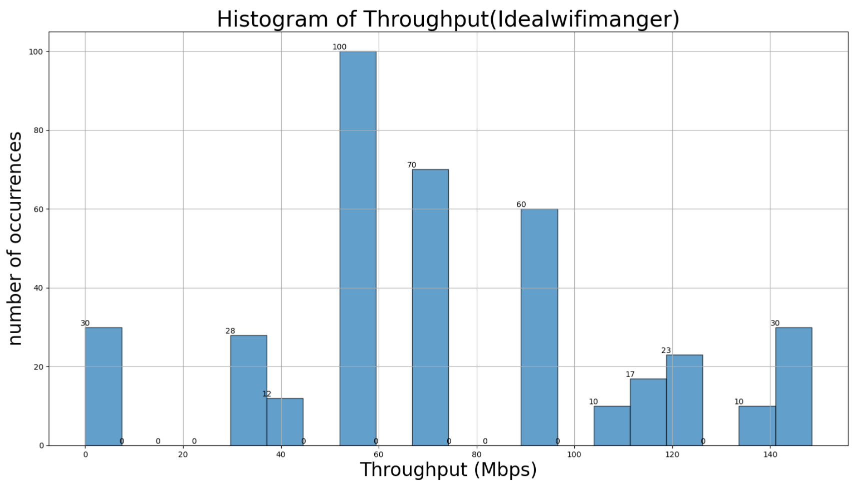

Figure 10: Histogram of throughput for Idealwifimanger

In the histogram (figure 10), it is evident that despite the simulation being conducted ten times, the obtained values fall within specific intervals. In the throughput histogram, the highest occurrences of results is in the range of 52 to 59 Mbps, corresponding to the throughput diagram's distance range of 240 to 330 meters

Now we turn to the analysis of the packet loss in the Idealwifimanger algorithm.(figure 11)

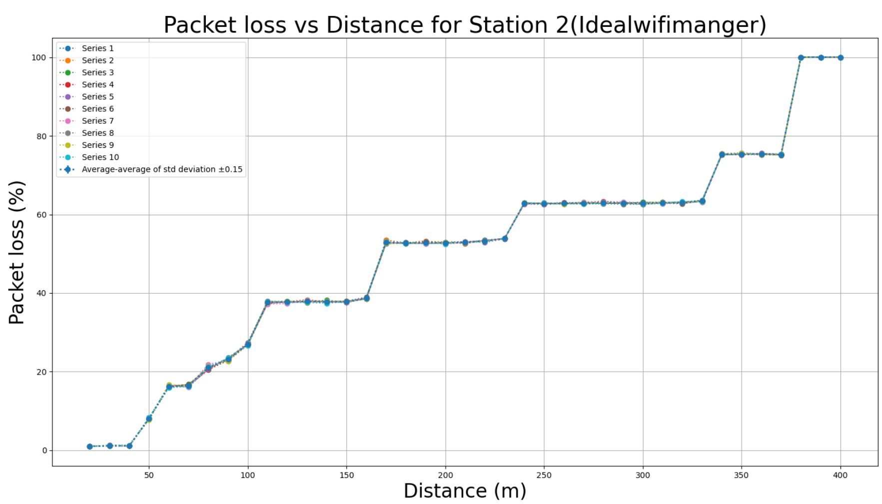

Figure 11: The packet loss plot for Idealwifimanger

As depicted in the figure 11, the packet loss was initially very low, around less than 2%, but it exhibited an upward trend with increasing distance. Eventually, it reached 100% at a distance of 380 meters. However, it is worth mentioning that it followed a consistent trend at some distances.

And next, we examine the packet loss histogram, as depicted in the figure 12.

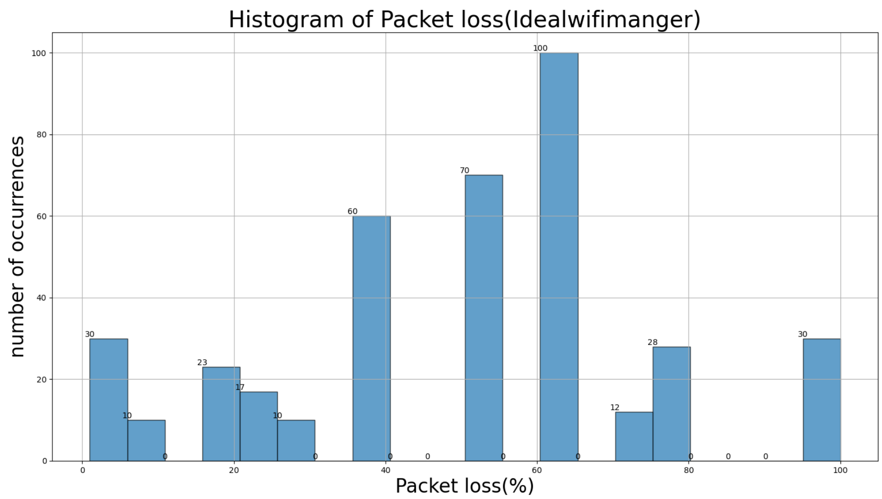

Figure 12: Histogram of packet loss for Idealwifimanger

In the packet loss histogram, the highest occurrences of results is in the range of 61% to 67% , precisely corresponding to the distance range of 240 to 330 meters where the rate control exhibited consistent behavior.

4.3 Minstrel-Ht

Following the previous trend, we first investigate the throughput, as depicted in the figure 13.

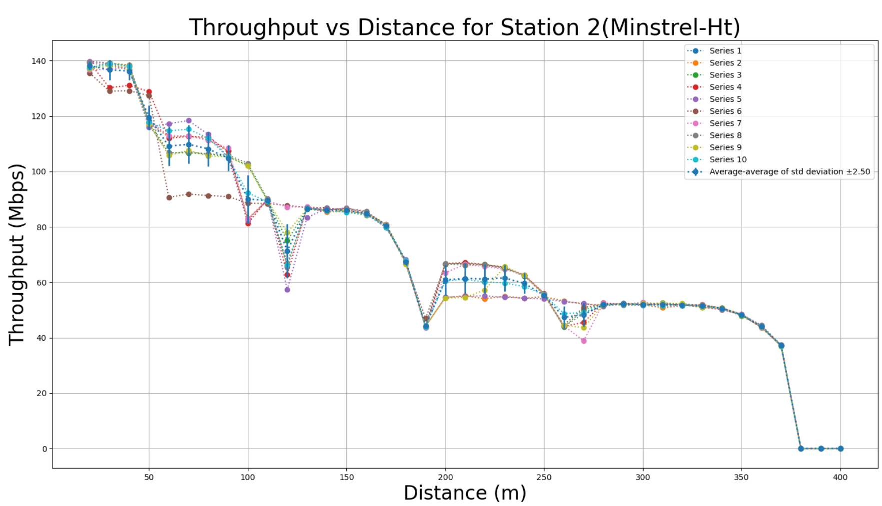

Figure 13: The throughput plot for Minstrel-Ht

The first noticeable aspect in the Minstrel-Ht throughput diagram (figure 13) is the significant difference compared to the previous state in utilizing random variables. Particularly, this difference is highly evident at certain points in the diagram, especially at distances below 270 meters. An important point to note is that the random variable has resulted in erroneous channel estimation at some points. For instance, Series 6 has exhibited significantly lower throughput compared to other series within the distance range of 60 to 100 meters. This discrepancy is attributed to the inaccurate channel estimation by the rate control, where the channel capacity may have been overestimated in this range, leading to excessive retries for best throughput utilization and consequent throughput degradation, or a very conservative approach has been taken, essentially underestimating the channel quality compared to what it actually was. This phenomenon has occurred several times, such as in the range of 190 to 250 meters, by Series 9, 7, 5, and 2.

Another notable observation in the diagram is the deviation from the continuous descending trend in throughput observed in the previous algorithm. Instead, in this diagram, in some intervals, a sharp increase followed by a return to its descending trend is observed. For example, this phenomenon is very evident at distances of 120 and 200 meters. This can be attributed again to the inaccurate channel estimation and the lack of feedback utilization, as highlighted earlier.

As mentioned earlier, the standard deviation is much higher than the previous state. Now, we move on to the analysis of Minstrel-Ht histogram of throughput(figure 14)

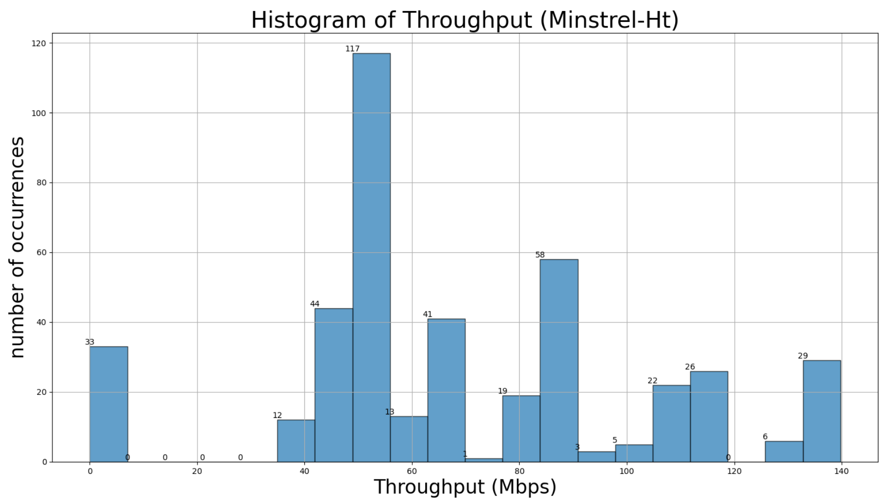

Figure 14: Histogram of throughput for Minstrel-Ht

The histogram illustrating throughput measurements depict a significantly wider range of values compared to the previous algorithm, indicating greater diversity in measured throughput. While some intervals exhibit staircase-like behavior as seen in the previous diagram, this characteristic is less pronounced in the Minstrel-Ht throughput histograms.

Now we turn to the analysis of the packet loss in the Minstrel-Ht algorithm.(figure 15)

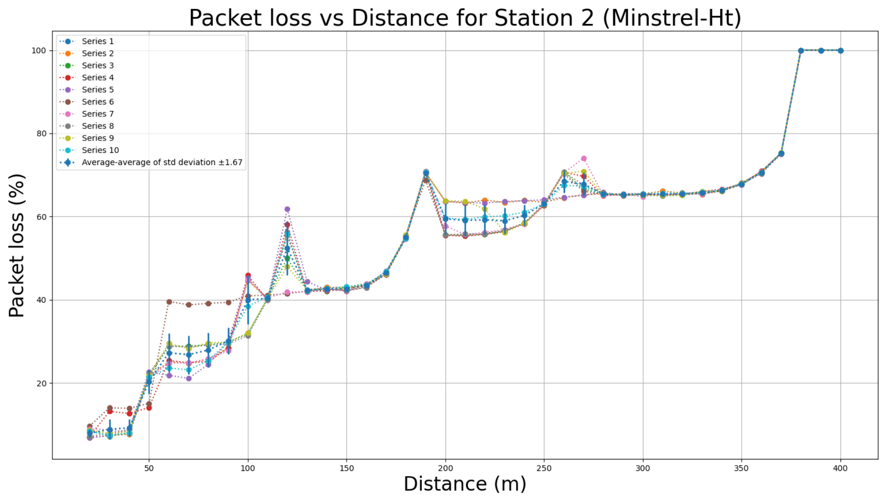

Figure 15: The packet loss plot for Minstrel-Ht

In the packet loss diagram (figure 15), a similar behavior to the previous diagram (figure 13) is observed. The percentage of lost packets varies significantly between different series at certain intervals, as discussed earlier regarding the reasons behind it. Additionally, unlike the previous algorithm, the packet loss has not been increasing in all intervals; instead, it has decreased in some cases.

As evident from the substantial differences between the various series, the average standard deviation has also been very high.

The figure 16 shows the packet loss histogram.

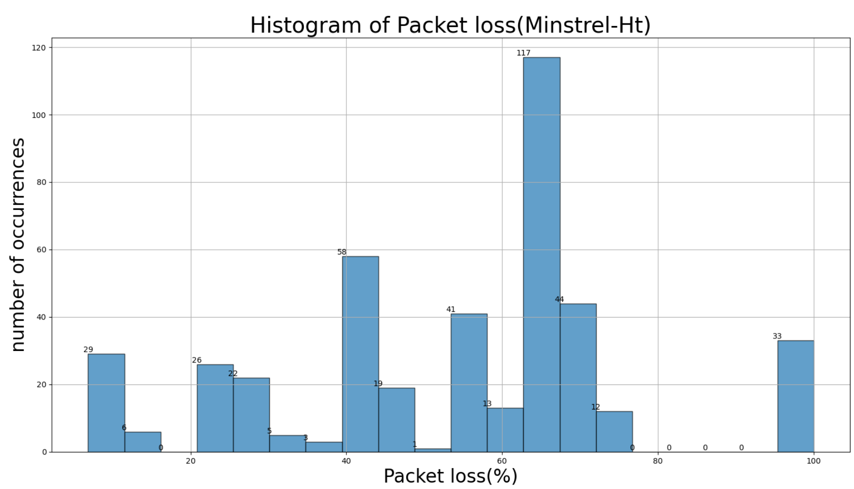

Figure 16: Histogram of packet loss for Minstrel-Ht

The histogram representing packet loss(figure 16) measurements also demonstrate a considerable diversity in measured values, surpassing that of the previous algorithm. Although some intervals display staircase-like patterns, this trend is less prominent in the Minstrel-Ht packet loss histogram. Notably, certain intervals, such as the range between 62% and 68% for packet loss, consistently exhibit the highest measured values.

4.4 Thompson sampling

We continue the previous trend for the Thompson sampling algorithm and start by examining the throughput, as illustrated in the figure 17.

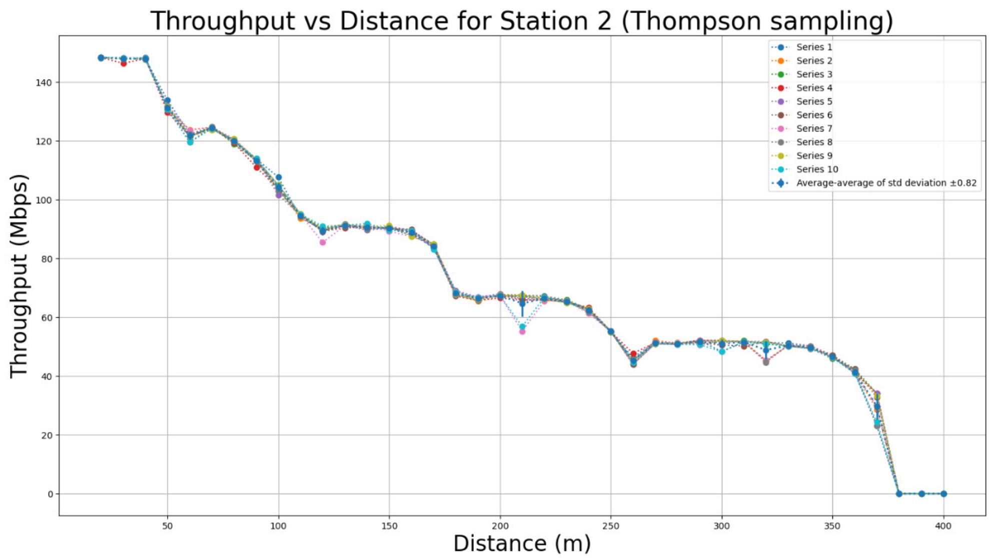

Figure 17: The throughput plot for Thompson Sampling

As observed in the Thompson Sampling algorithm's throughput diagram (figure 17), it is evident that the random variables have had a significant impact on the overall trend. However, this difference compared to the Minstrel state is much less pronounced, and the average standard deviation is also much lower. Generally, the diagram shows a decrease in throughput with increasing distance, except at the distance of 260 meters, where it appears that the rate control has experienced a disruption in accurately detecting the rate, and thereafter, the decreasing trend continued until the throughput reached zero at a distance of 380 meters. It is worth noting that the measured throughput value at a distance of 20 meters was 148 Mbps, similar to the Idealwifimanger algorithm. We have the throughput histogram as shown in the figure 18.

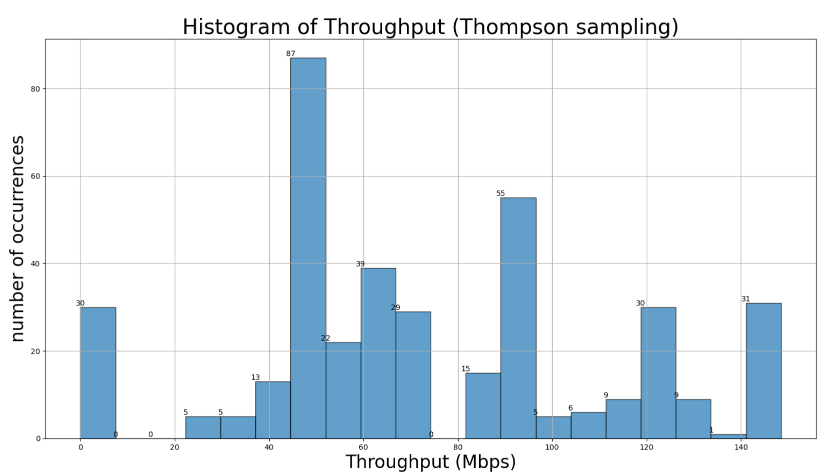

Figure 18: Histogram of throughput for Thompson Sampling

Figure 18 illustrates that the range of values in the throughput histogram exceeds that of the IdealWifi-Manager algorithm. Peaks are still observed in specific intervals, notably between 50 and 57 Mbps.
We proceed to investigate the packet loss associated with the Thompson Sampling algorithm, as depicted in the figure 19.

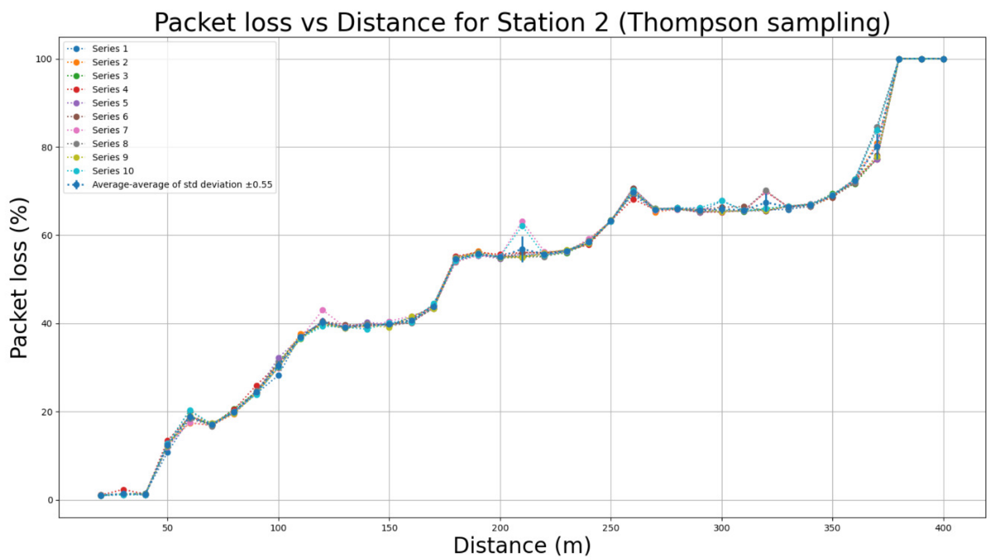

Figure 19: The packet loss plot for Thompson Sampling

In the packet loss diagram (figure 19), a trend of increasing packet loss percentage throughout the simulation is noticeable. It starts at less than 2% at a distance of twenty meters and gradually increases until reaching 100% at a distance of 380 meters. Additionally, at the distance of 260 meters, this trend undergoes a change, indicating a disruption in rate selection by the rate control, leading to an increase in the percentage of lost packets. However, the rate control corrects this trend in subsequent measurements. Another noteworthy point is the sensitivity to random variables, which is relatively high compared to the Idealwifimanger scenario, as evident in the average standard deviation.

The figure 20 shows the packet loss histogram.

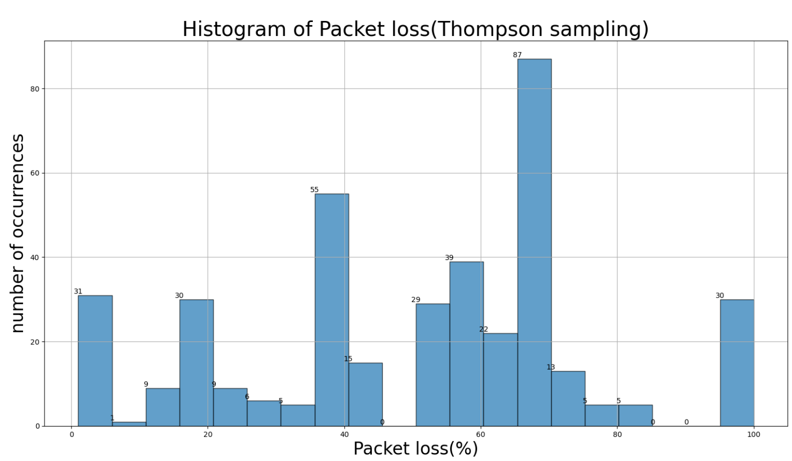

Figure 20: Histogram of packet loss for Thompson Sampling

Figure 20 depicts higher ranges of values in the packet loss histogram compared to the IdealWifiManager algorithm. Peaks persist in certain intervals, particularly within the range of 62% to 69%.

4.5 Simulation Results

As previously mentioned, in our project, for the constant rate algorithm, we assumed that at each distance, the highest throughput level and the lowest packet loss percentage are considered. The resulting plot is compared with other rate control algorithms.We begin by examining the throughput, as illustrated in the figure 21.

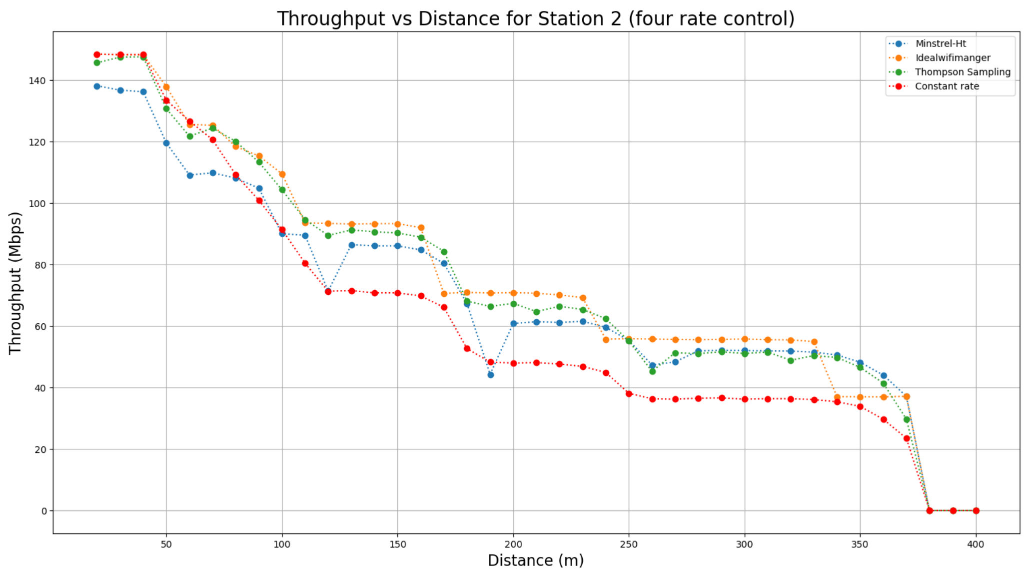

Figure 21: The throughput plot for all four rate control algorithms

Upon initial examination of the figure 21 , it becomes apparent that the constant rate undergoes a significant decrease with increasing distance. Even though its performance closely resembles the ideal algorithm, especially up to a distance of 50 meters, a noticeable decline in throughput occurs beyond the 100 meters.

This discrepancy arises from the fact that other rate control algorithms utilize methods that enable them to adapt more optimally to scenarios where snr decreases and distances increase. These algorithms leverage feedback or other mechanisms to adjust transmission rates dynamically, unlike the manual adjustments made in the constant rate scenario.

Now, turning our attention to the other rate control algorithms, it's observed that initially, both the IdealwiFimanager and Thompson sampling exhibit superior performance compared to Minstrel-Ht. This superiority stems from the close-loop nature of these two algorithms, which utilize feedback for rate adjustments, resulting in more accurate estimations of channel conditions in the initial distances.

The performance of Thompson sampling and IdealwiFimanager remains comparable up to a distance of 160 meters, after which both experience a decrease in throughput with increasing distance. Meanwhile, Minstrel-Ht generally demonstrates inferior performance in terms of throughput up to 160 meters, although it should be noted that Minstrel-Ht experiences disruption around the 120 meters, which is resolved in subsequent measurements (discussed further in the Minstrel simulation section).

However, a noteworthy observation occurs at the 170 meters, where both Minstrel-Ht and Thompson sampling exhibit better throughput than the Idealwifimanger algorithm. This behavior is attributed to the stringent BER requirements in the Idealwifimanger algorithm, which must always be lower than a specified threshold. This requirement leads to the observed behavior at this point, a phenomenon that also repeats at the 240 meters and 340 meters distances.

It's important to note that Minstrel-Ht encounters disruption again at the 190 meters. However, a significant aspect regarding Minstrel-Ht is its convergence to the throughput received by the receiver, which closely matches that of the other two rate control algorithms, even becoming the best performer at distances between 340 meters to 360 meters.

Ultimately, all four rate control algorithms converge to zero throughput at the 380 meters.

We now proceed to analyze the histogram of throughput(figure 22). It is important to note that, due to the repetitive nature of measurements in the constant rate algorithm, where values are determined based on the configured rate, the power measurements and packet loss values may be duplicated. This repetition could potentially introduce complexity and misinterpretation for readers of the article. As a result, this section has been excluded, and we will concentrate on scrutinizing the histogram plot of the IdealwiFimanager, Minstrel-Ht, and Thompson sampling rate control algorithms.

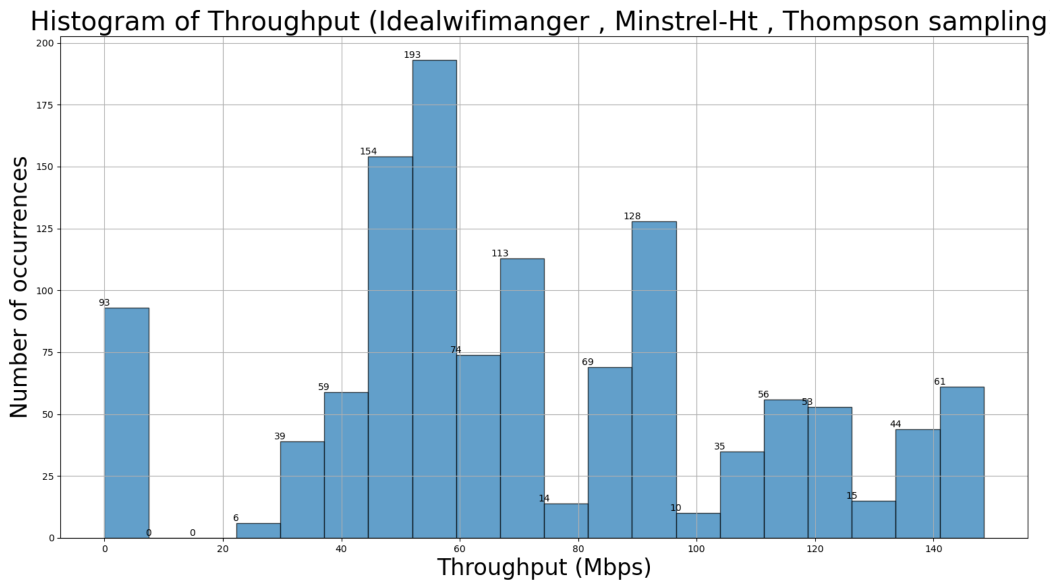

Figure 22: Histogram of thrughput for Idealwifimanger, Minstrel-Ht, Thompson sampling

As evident from the histogram (figure 22), the most frequent range of measured throughput values for the three rate control algorithms lies between 52 to 59 Mbps , as depicted in the graph. Another notable range is 141 to 148 Mbps , as also observed in the throughput diagram. In this range, only the Idealwifimanager and Thompson sampling rate control algorithms have recorded measurements, considering that each experiment was conducted 10 times and each rate control measured values within this range in at least the first three distances.

Lastly, attention is drawn to the range of 22 Mbps to 29 Mbps , where only the Thompson sampling algorithm has yielded results six times. Utilizing this histogram, the distribution of measured values throughout the throughput-related simulations can be elucidated.

Now, under similar conditions as initially described, we turn to examine the packet loss.(figure 23)

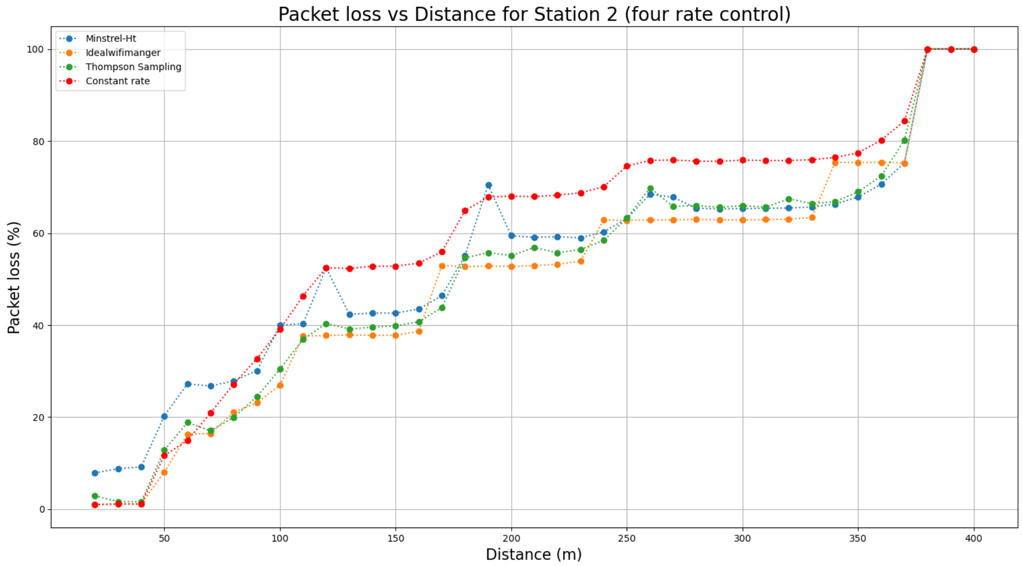

Figure 23: The packet loss plot for all four rate control algorithms

In the packet loss plot(figure 23), in the initial distances, the packet loss percentage of the constant rate is similar to that of the IdealWiFiManager and Thompson Sampling. However, with increasing distance, this percentage increases compared to the other rate control algorithms. Minstrel-Ht also initially measures a higher percentage compared to the other three algorithms. Additionally, it encounters two disruptions at distances of 120 meters and 190 meters, leading to a significant increase in packet loss percentage at these distances. However, thereafter, it demonstrates significantly better performance and even exhibits the lowest packet loss percentage in the range of 340 meters to 370 meters when compared to the other algorithms.

Regarding the IdealWiFiManager and Thompson Sampling algorithms, their performance is very similar to each other, with the Ideal WiFi Manager generally performing better. However, at distances of 170 meters, 240 meters, and in the range of 340 meters to 370 meters (as previously mentioned), Thompson Sampling exhibits a lower packet loss percentage.

Finally, all four rate control algorithms converge to 100% packet loss at the 380 meters.

In the packet loss histogram, similar to the throughput histogram, Constant rate has been removed, resulting in the figure 24.

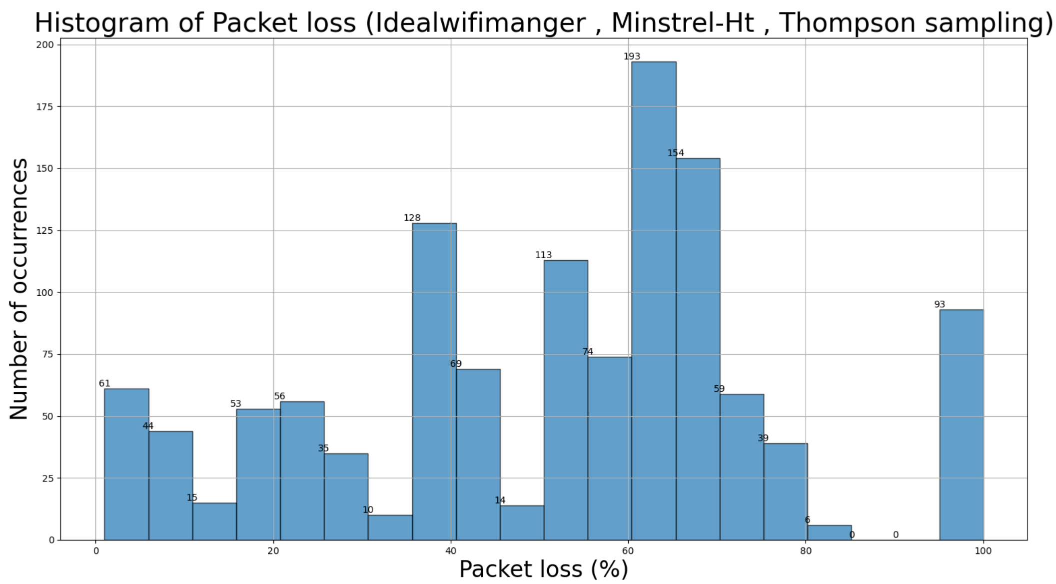

Figure 24: Histogram of packet loss for Idealwifimanger, Minstrel-Ht, Thompson sampling

In the histogram related to packet loss(figure 24), it is also observed that the most frequent range of values obtained for packet loss for all three rate control algorithms lies between 61 to 68 percent. The minimum packet loss value, as seen in the packet loss diagram, corresponds to the range of zero to seven percent, where the Ideal WiFi Manager and Thompson Sampling rate controls have yielded the lowest values.

In the last class before packet loss reaches one hundred percent (referring to the range of 80 to 87 percent), measurements within this range have occurred six times, with all six instances attributed to the Thompson Sampling algorithm.

5 Conclusion

In this project, we investigated various rate control algorithms in the IEEE 802.11ac standard. As observed, the Close-Loop rate control algorithms exhibited better performance, both in terms of higher throughput and lower packet loss percentage, especially at shorter distances. However, it should be noted that with increasing distance, Minstrel-Ht also demonstrated good performance and even outperformed other rate control algorithms in some distances.

Considering the nature of Thompson sampling algorithm, which utilizes feedback from the receiver to quickly adapt to channel variations and the absence of interference observed in this algorithm in rate selection, unlike Minstrel-Ht, which experienced interference multiple times at different distances during simulation, and also the absence of definition for the BER threshold, as defined in the Ideal WiFi Manager, which was shown to degrade the performance of this rate control in some cases, it can be generally stated that Thompson Sampling exhibited the best performance in this project.

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