6.829 Final Project: A comparison of bit rate selection algorithms

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Abstract

We compare the performance SampleRate and Minstrel, two popular bit rate selection algorithms that have widespread real-world usage. We use a trace-based approach to avoid kernel programming and improve reproducibility and allow analysis. We test both algorithms in multiple real-world scenarios, including scenarios with mobile clients and noisy environments, to highlight differences between the two. We also introduce improvements to the Minstrel algorithm that allow for significant gains in throughput.

1 Introduction

One of the key ways that wireless networks differ from wired is that wireless networks have varying link rates. Link conditions vary with time due to interference from other devices, changing network geometry, and mobile clients. An optimal rate at one time may be different from the optimal rate just 30 seconds earlier. A good bit rate selection algorithm has to detect and adapt to these conditions. If the chosen bit rate is too slow, then the throughput will be unnecessarily low; if the rate is too high, failures will be very frequent and throughput will again suffer.

The wireless 802.11 standard includes a variety of different bit rates to account for a range of possible network speeds. Later standard versions introduce more bit rates; we focus on bit rates available in 802.11b and 802.11g, since 802.11n networks and hardware were not available for study. Table 1 lists the bit rates available in the wireless networks studied. The job of a bit rate selection protocol is to choose a bit rate, from among the available rates, for each packet transmission. Due to the variability and non-determinism of packet transmission, this is a challenging task.

Throughput	Transmission	Modulation
1 Mbps	dsss	bpsk
2 Mbps	dsss	qpsk
5.5 Mbps	dsss	cck
11 Mbps	dsss	cck
6 Mbps	ofdm	bpsk
9 Mbps	ofdm	bpsk
12 Mbps	ofdm	qpsk
18 Mbps	ofdm	qpsk
24 Mbps	ofdm	qam-16
36 Mbps	ofdm	qam-16
48 Mbps	ofdm	qam-64
54 Mbps	ofdm	qam-64

Table 1: Bit rates available in 802.11b and 802.11g. The first block, of four bit rates, contains bit rates introduced in 802.11b, while the last eight bit rates were introduced in 802.11g.

There are three main classes of bit rate selection protocols: frame-based, SNR-based, and cross-layer protocols. Frame-based protocols measure the fraction of successfully received packets. SNR protocols make decisions based on the estimated Signal to Noise ratio. Cross-layer protocols use SoftPHY data from the physical layer to make better estimates of bit rate properties. The most commonly implemented protocols on today's networks are frame based; SNR protocols perform poorly [1] and cross-layer protocols are hard to deploy due to their violation the standard network layering abstraction. Due to their ubiquity, we analyze frame-based protocols.

The two most popular frame-based protocols are SampleRate and Minstrel. Both were implemented in the MadWifi drivers for Linux wireless, and today Minstrel is the default bit rate selection algorithm for all wireless drivers on Linux. We use a trace-based approach to analyze the performance of these two algorithms. We also created a modified version of Minstrel that provides significant throughput gains over the vanilla Minstrel implementation.

We provide a high-level overview of SampleRate and Minstrel in Sections 2 and 3. Then we discuss our testing methodology in Section 4 and analyze the results in Section 5. Finally we introduce our modifications to the Minstrel algorithm in Section 6 and analyze the performance of our improvements.

2 SampleRate

SampleRate, first introduced in [1], is a bit rate selection algorithm which maintains estimates of average transmission time for each potential bit rate. To keep these estimates up to date, SampleRate periodically sends a packet at a randomly-selected bit rate, and uses the success or failure of this packet to update the average transmission time of that bit rate. SampleRate also abandons a bit rate after four successive failures at that rate. All information about packets is maintained with a 10-second sliding window.

SampleRate has three main functions: `ApplyRate()`, which returns a the bit rate to send a packet at, `ProcessFeedback()`, which updates the statistics for a bit rate after an attempted packet send, and `RemoveStaleResults()`, which removes the effect of packets older than 10 seconds.

3 Minstrel

Minstrel, developed specifically for the Linux kernel, attempts to improve upon SampleRate to make it better suited for noisy or dynamic environments. Unlike SampleRate, Minstrel tracks raw probabilities of successful transmission for each bit rate, computed based on an exponentially-weighted moving average of 100ms windows.

Minstrel makes use the multi-rate retry chain (MRR), an array of bit rates and number of attempts to make at each bit rate, that tells the card which rates to try before reporting a failure. The retry chain makes failures extremely unlikely and allows Minstrel to choose fall-back rates when a packet does not succeed. When not sending a probe packet, Minstrel sets the MRR to first try the rate with the highest throughput, then the next-highest throughput, then greatest probability of success, and finally attempts to send a packet at the lowest base rate. In essence, Minstrel tells the card to send at the highest throughput rates but to fall back to reliable rates upon failure.

To keep an accurate estimate of throughput and probability for each rate, Minstrel sends sample frames ten percent of the time. However, Minstrel tries to avoid sampling at a rate slower than the current best rate. If the randomly chosen rate has a higher lossless throughput than the current optimal rate, the MRR first lists the sample rate, then the highest-throughput rate, then the best-probability rate, and finally the base rate. On the other hand, if the random rate is slower than the optimal rate, the sample rate is placed lower in the retry chain: first, the best throughput rate is tried, and only if it fails does the sample rate then get attempted (followed, as usual, by the best probability rate and the base rate). This ensures that Minstrel never samples rates worse than the current optimal rate unless the optimal rate experiences a failure. See Table 2 for an overview of the retry chains used in Minstrel.

Minstrel implementation is based on SampleRate, so it also has `ApplyRate()` and `ProcessFeedback()` methods, as well as a `UpdateStats()` method that runs every 100ms. `UpdateStats()` is home to some of the key differences between Minstrel and SampleRate. Instead of making decisions based on the average transmission time, Minstrel uses throughput, computed with

$$T = \frac{p}{\texttt{tx\_time}}$$

where T is the throughput of some rate r, p is the probability of successfully transmitting at r, and tx_time is the computed lossless transmission time at rate r.

The probability p of a successful transmission is calculated from statistics collected by the `ProcessFeedback()` method, and is done using an exponential weighted moving average, or EWMA. The EWMA creates a weighted average that weighs recent data more heavily than old data, with the weighting for old data decreasing exponentially. An EWMA ensures that a sudden degradation in link quality will create a rapid response in the probabilities, making Minstrel perform better in dynamic environments. Minstrel will waste less time sending packets at a rate that no longer works, as compared to a simple sliding-window probability calculation.

4 Methodology

We collected traces about the success rates of each bit rate through a modified Linux wireless driver; Minstrel and SampleRate were then re-implemented in Python and replayed on this collected data.

4.1 Motivation

Our initial plan was to use the algorithms as implemented in the MadWifi drivers for the Atheros chip. However, MadWifi is deprecated, and only runs on very old network cards. In addition to the unavailability of compatible hardware, MadWifi would not be an accurate reflection of contemporary users. Both ath5k and `ath9k`, which were created to replace MadWifi, did not port the old bit rate selection system

Try	Normal	Random (slower than best)	Random (faster than best)
1	Best throughput	Best throughput	Random
2	Next best throughput	Random	Best throughput
3	Highest probability	Highest probability	Highest probability
4	Lowest rate	Lowest rate	Lowest rate

Table 2: Multi-rate retry chains for Minstrel

from MadWifi and instead opted to use the Linux kernel's rate selection framework, which only implements Minstrel. Porting SampleRate over to the new drivers would not have been trivial, as there are vast differences in the interfaces.

At this point, we decided to take a different approach and use an approach similar to that used in Sprout [3]. We modified the `ath9k` driver to try bit rates uniformly and report packet successes and failures, then analyze this data in user-space with re-implementations of SampleRate and Minstrel. Not only did this lessen the re-implementation cost (since the algorithms were re-implemented in user-space in Python, not in kernel-mode in C), but it also provided reproducibility and allowed us to investigate modifications to SampleRate and to Minstrel.

4.2 Trace Collection

Traces were collected from an `ath9k` driver modified to sample bit rates uniformly and to report successes and failure from each packet. Each bit rate was sampled uniformly in time — thus, more packets were sent at higher bit rates, since those bit rates deliver packets faster. For each packet sent, we recorded the time it was sent, the bit rate it was sent at, and whether or it it succeeded. The bit rate for the next trace packet was chosen to be the bit rate that had the smallest total transmission time so far. This guarantees approximately uniform selection of bit rates. The wireless card used was an Qualcomm Atheros `AR9285` Wireless Network Adapter.

Traces were collected at an unused access point in a basement of MIT. Before initiating trace collection, the wireless card was put in monitor mode for a minute to check that no other users were connected to the access point. None were, guaranteeing that traces would not include delays from carrier sensing or run into problems due to congestion at the access point. Traffic was simulated by sending 1500 byte packets to the access point's IP address. Packets were sent over UDP to avoid the TCP congestion window and retry loop. Figure 1 shows a floor plan of the access point and basement.

Eighteen total traces were collected, grouped into a number of scenarios. Each trace was 30 seconds to a minute long, and each scenario was repeated twice. One scenario placed the wireless card with line of sight to the access point, two meters from it. Another created solid body interference by having one of the authors stand between the wireless device and the access point. One placed the device around a corner from the access point, creating some potential for multi-path interference and fading. In one scenario, we moved the wireless device throughout the trace, pacing back and forth in a 10 meter line in front of the access point. Finally, one five-minute trace was taken, which mixed the above scenarios, first moving around a corner, then standing still, then moving to line-of-sight with the access point. A few shorter (3 to 15 second long) traces were collected to investigate the startup behavior of bit rate selection.

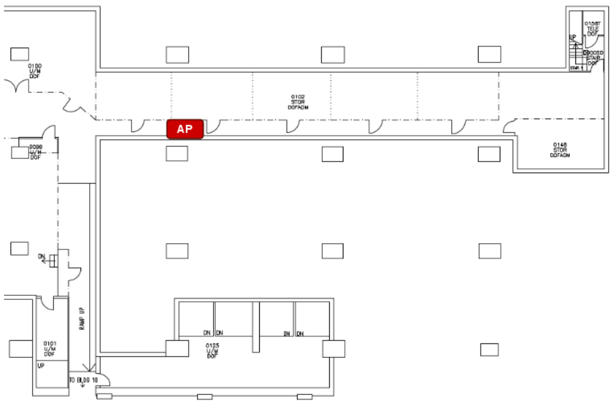


Figure 1: We collected most traces at a remote access point in the basement of MIT's Building 13.

4.3 Testing framework

Once collected, traces were fed to a bit rate selection simulator to analyze the performance of Minstrel and SampleRate. `harness.py` interfaced with the bit-rate selection algorithms using two functions: `ApplyRate()` and `ProcessFeedback()`. `ApplyRate` returns a multi-rate retry chain of rates to attempt transmission at. The retry chain is one element long for SampleRate, since it does not use MRR. `ProcessFeedback` is a callback that is passed the success or failure of the transmission and how many attempts were made at each bit rate. This parallels the interface used by the Linux kernel itself. For every packet transmission, the simulator would call `ApplyRate`; compute the probability of success based on packets sent in 10-millisecond window around the current time; and from that determine the success or failure of the packet, and the number of retries it required.

We implemented SampleRate as outlined in John Bicket's Master's thesis [1]. This implementation is slightly different from how it was implemented in the MadWifi kernel driver. The primary difference is that the kernel implementation uses a EWMA, while the thesis implementation computes average transmission times based on a 10-second sliding window. It would be worth looking at the performance of EWMA-based SampleRate in the future. Our implementation, `samplerate.py` contains `ApplyRate()`, `ProcessFeedback()` and `RemoveStaleResults()`, as well as a few helper functions and data structures for tracking rate statistics.

We implemented Minstrel by porting the C code from the 3.3.8 version of the Linux kernel into Python. `minstrel.py` contains `ApplyRate()`, `ProcessFeedback()` and `UpdateStats()`, as well as a few helper functions and data structures for tracking rate statistics.

To improve re-implementation fidelity, both implementations were meticulously checked by both authors.

4.4 Experimental parameters

There are a few parameters that can be adjusted in Minstrel and SampleRate, but our implementation is consistent with what the respective authors originally chose.

In SampleRate, the number of successive retries, the frequency of probe packets, the window size, and the lossless *tx_time* estimations are all parameters that can be changed. The SampleRate thesis chose 4 successive retries, a probe frequency of every ten packets, and a window size of ten seconds. We used the same values in our implementation. Additionally, we use the same equation to calculate *tx_time*.

In Minstrel, the frequency of probe packets, the window size, and the EWMA weighting are the adjustable parameters. The 3.3.8 Linux kernel uses a probe frequency of 10%, a window size of 100ms, and a EWMA weighting of 0.75. We use the same values. Additionally, Minstrel also estimates *tx_time* using the `ieee80211_frame_duration()` method from the `util.c` file in `net/mac80211`. We implemented the same function in Python.

5 Analysis

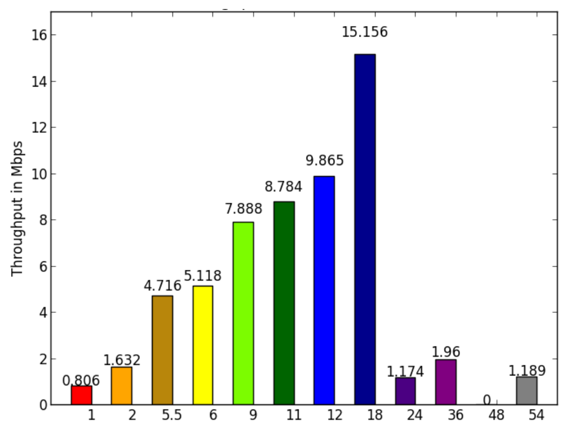
Minstrel and SampleRate perform similarly, usually within 3 Mbps of each other. We were slightly surprised to see how significantly SampleRate outperformed Minstrel in certain situations, though, with throughput being up to 67% higher. However, in especially noisy situations, such as when the client is moving or when the client is around the corner from the access point, Minstrel consistently outperforms SampleRate. Figure 2b shows the results of a single run of both Minstrel and SampleRate over all the different types of traces we collected. This is consistent with the literature—the authors of Minstrel noted that they focused on making Minstrel robust to poor conditions [2], which means losing potential throughput gains in stable situations. Conversely, John Bicket noted that SampleRate performs better in stable situations than noisy or highly varying conditions [1].

In Figure 2a we show the performance of constant bit rates on the `clear_1.dat` trace, which is a 35 second trace in clear view of the access point. The optimal rate here was 18 Mbps, which achieved an average throughput of about 15 Mbps. The next highest bit rate, 24 Mbps, shows a large plummet in performance, down to a throughput of 1.17 Mbps. This steep drop is characteristic, and is also talked about in the SampleRate thesis [1]. It demonstrates just how important bit rate selection is — the optimal bit rate has typically much higher throughput than the next-best rate, but if the algorithm strays too high the results can be devastating.

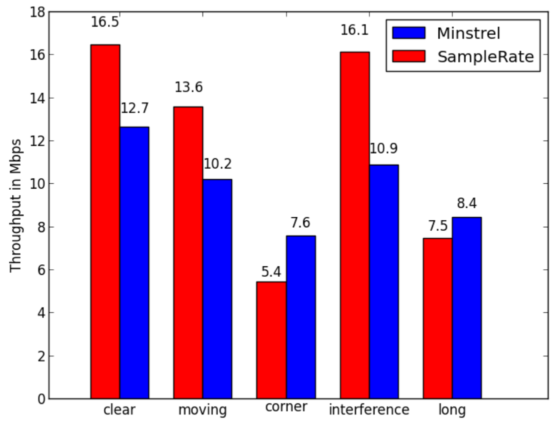
Bit rate selection algorithms strive to have a throughput near or greater than the optimal constant rate. For this `clear_1.dat` trace, SampleRate clearly meets this goal, achieving an average throughput more than 1 Mbps higher than the optimal constant rate. In noisier situations, though, Minstrel tends to be closer to the optimal constant rate.

Bit rate selection algorithms naturally show variation between runs on the same data because probe rates are chosen randomly. The variations were small, though. On ten runs on the `clear_1.dat` trace, the average of Minstrel over 10 runs was 7.52 Mbps, with a maximum variation of +/- 0.12 Mbps. SampleRate was similarly stable, it averaged 5.284 Mbps over 10 runs, with a maximum variation of about +/- 0.3 Mbps. The variation of results on other traces (except for traces 5s or less) was similar.

The histograms of which rates the algorithms de-



(a) Throughput of using a constant 802.11b/g bit rate in clear line-of-sight from the access point.



(b) Throughput of Minstrel and SampleRate in various scenarios.

Figure 2: Comparing Minstrel and Samplerate

cided to send at provided some useful insight into their behavior. Table 3 is a histogram of a 35 second corner trace. In this situation Minstrel outperforms SampleRate. The constant rate throughputs demonstrate that 11, 12 and 18 Mbps were the optimal rates to send at, and that no packets were successful at any higher rates. SampleRate does not use these rates except for probe packets, which happens once every ten seconds. Minstrel, since it does not terminate transmission after four successive failures, spends a lot of time sending probe packets at these high rates, which are never successful. The only reason low rates have fewer probe packets is because Minstrel explicitly places them second in the retry chain. Despite the fact that SampleRate spends less time probing high rates, it is less successful. This is because Minstrel send the most packets at the three most successful bit rates. SampleRate, however, spends too much time sampling low bit rates. Additionally, it spends a lot of time sending at 5.5 Mbps, which is not one of the optimal rates. We suspect that this might be because the equation SampleRate uses to estimate average transmission time needs to be tweaked.

Our examination of the histograms showed us that Minstrel spends a lot of time sampling at high rates. In the specific case we examined, they were all probe packets. But sometimes Minstrel would choose 54 Mbps as the rate with the best throughput, which made little sense. A closer investigation revealed that Minstrel would sometimes get lucky with a successful probe at 54 Mbps. The probability of success would be 1, so then 54 Mbps would be chosen as the rate with the best throughput. This is unfortunate, but the real harm comes in the next window: all non-probe packets would now be sent at 54 Mbps, and nearly all would fail. However, since these hundreds of failed packets weight equally with the single successful probe packet, Minstrel still considers 54 Mbps the best rate. Thus the probability of success might drop from 1 to about 0.70, which is still high enough for the throughput equation to rank 54 Mbps highly. Fundamentally, the problem is that the EWMA does not account the second block having hundreds more packets than the first, so the probabilities were not declining fast enough after a large number of failures.

Additionally, Minstrel uses a complex method of calculating when to send a sample packet that involves a heuristic to make sure that 10% of packets were actually samples. This is because the MRR places sample packets second in the retry chain when the sample rate is slower than the rate with the best throughput. So even if 10% of probes have a sample rate in the retry chain, a sample rate is not actually sent 10% of the time. We implemented this heuristic and it tended to cause Minstrel to send too many probe packets.

In the next section we will talk about Minproved, an improved version of Minstrel where we attempt to fix problems with EWMA and too-frequent probing.

6 Improvements to Minstrel

In Section 5, we noted that the EWMA used by Minstrel causes problems when probe packets succeed. A natural next step was to modify Minstrel to avoid this problem, by weighing each 100ms block of statistics in proportion to how many packets it contains. To preserve the exponential weighing of statistics, we chose to weigh each 100ms block based on the number of packets sent, compared to the those sent in the average block. Parameters were chosen so that if all blocks were of average size, our “balanced” EWMA would behave identically to a normal EWMA.

To achieve, this weighing, we first recast the usual EWMA algorithm. The usual algorithm computes

$$p \leftarrow \alpha p + (1-\alpha)\frac{n_i}{d_i}),$$

where p is the probability, α is a weight factor equal to 0.75 in Minstrel, and n_i and d_i are the number of successful and total packets in the 100ms window. We next write this as

$$p \leftarrow \frac{\beta p + \frac{n_i}{d_i}}{\beta + 1},$$

where $\beta = \alpha/(1-\alpha)$. We can now change the factor in front of n_i/d_i to account for the total number of packets sent. In our case, we chose to compute

$$p \leftarrow \frac{\beta p + w_i\frac{n_i}{d_i}}{\beta + w_i},$$

where the weight w_i is $d_i/(d/b)$, with d the total number of packets ever sent and b the total number of 100ms windows ever seen. Then d/b is the average number of packets per window and $d_i/(d/b)$ is the ratio between the current window and the average window. Note that if the current window is of average size, this is exactly equal to the usual EWMA result. Finally, we can simplify the above equation to

$$Sp \leftarrow \frac{\beta\frac{d}{b}Sp + Sn_i}{\beta\frac{d}{b} + d_i},$$

where S is any constant. This equation is usable in fixed-point arithmetic (where S is the scaling factor for the fixed-point representation), making it suitable for implementation in the Linux kernel (which avoids floating point computations for portability reasons). Because packets at high rates rarely succeed, the average window size is a few packets. The main qualitative difference between our balanced EWMA and the original Minstrel EWMA is that windows with many more packets than the average for that bit-rate are weighted extraordinarily heavily. This fact allows us to avoid multiple failing 100ms windows.

We tested a modified Minstrel which used this more balanced EWMA algorithm on the same traces as Minstrel and SampleRate, and found a consistent improvement of approximately 1 Mbps over the normal Minstrel algorithm.

As noted in Section 5, Minstrel sends sample packets too frequently. This is due to a flag the kernel uses to track whether a probe bit rates was actually sampled. Recall that if the sample rate is slower than the current best rate, it is second in the retry chain, so there is a good chance that the random rate will never be used to send a packet. This system is used as an attempt to make sure that 10% of the sent packets are actually probes, as opposed to simply having 10% of packets contain a random rate somewhere in the retry chain. The flagging seems to misbehave, causing the extremely aggressive probing we see in some traces. For example, in one of the traces where the client was around a corner from the access point, Minstrel sent almost half of its packets at probe frequencies. We modified Minstrel to be less aggressive with probe packets. We eliminated the flagging system, and instead simply put a random bit rate in 10% of packets. This lead to a very large throughput improvement, bringing Minstrel to the same level of performance as SampleRate, and greatly exceeding it on noisy traces such as the cases where the client was around a corner or moving. When this change was paired with the balanced EWMA change, it consistently outperformed both vanilla Minstrel and SampleRate.

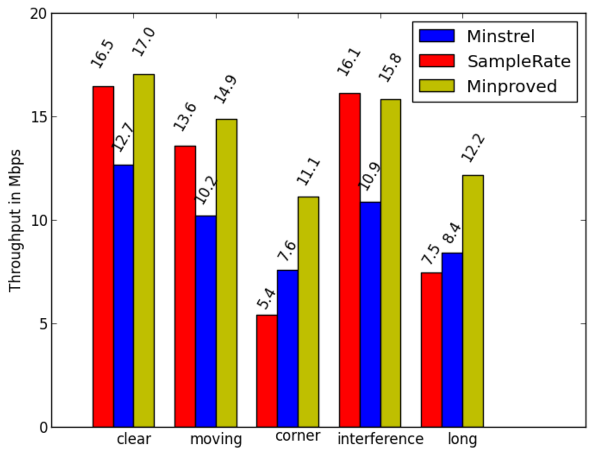


Figure 3: Throughput of Minproved as compared to SampleRate and vanilla Minstrel.

Overall, our improved Minstrel, which we call Minproved, often out-performs Minstrel by multiple Mbps and never doing any worse; and usually surpassing the best constant bit rate. In only one case did SampleRate achieve higher throughput than Minproved, and in this case both surpassed the best constant bit rate. In cases where Minstrel out-performed SampleRate, the same behavior was true of Minproved. In most cases, Minproved was 30% faster than Minstrel, and in some the improvement as great as 60%.

Maximum Throughput	**SampleRate**	**Minstrel**	**Minproved**	**Static Throughput**
1 Mbps	631 pkts	39 pkts	29 pkts	0.639 Mbps
2 Mbps	863 pkts	82 pkts	20 pkts	1.425 Mbps
5.5 Mbps	4814 pkts	110 pkts	805 pkts	4.406 Mbps
6 Mbps	423 pkts	137 pkts	276 pkts	4.603 Mbps
9 Mbps	553 pkts	327 pkts	57 pkts	4.630 Mbps
11 Mbps	3326 pkts	4121 pkts	3356 pkts	9.627 Mbps
12 Mbps	4649 pkts	9515 pkts	14285 pkts	9.444 Mbps
18 Mbps	1154 pkts	13295 pkts	15795 pkts	8.458 Mbps
24 Mbps	16 pkts	6909 pkts	1918 pkts	0 Mbps
36 Mbps	16 pkts	6944 pkts	2030 pkts	0 Mbps
48 Mbps	16 pkts	6888 pkts	2009 pkts	0 Mbps
54 Mbps	16 pkts	7308 pkts	1953 pkts	0 Mbps
Avg. Throughput:	*5.42 Mbps*	*7.578 Mbps*	*11.107 Mbps*	

Table 3: Histograms of the number of packets sent at each rate. The trace was `corner_1.dat` and was recorded around the corner from the access point. The best fixed rate for this trace was 11 Mbps, which achieved a throughput of 9.627 Mbps. Minproved achieves a higher throughput than the best fixed rate.

However, Minproved still makes many poor choices. While a single successful probe packet does not cause many hundreds of milliseconds of failed packets, as it does in Minstrel, the single successful packet can still cause one window's worth of failed packets. Instead, it would be best if a successful probe packet at a rarely-successful bit rate was treated more carefully. One can imagine an algorithm, for example, which would treat a single successful probe packet as a reason to send a dozen more probe packets at that bit rate, but does not yet commit to sending hundreds of packets at that bit rate.

However, these are only vague ideas, and we have no concrete implementations of such an algorithm.

7 Availability

All of our code and collected trace data are available on GitHub:
`https://github.com/pavpanchekha/6.829-project/tree/3.8.6`

This repository contains the modified `ath9k` driver used to collect the traces, the traces we collected, as well as the Python simulation framework.

8 Future Work

Very little analysis has been done of the performance of bit rate selection algorithms on 802.11n networks. 802.11n introduces many new rates, as well as multiple-input/multiple output (MIMO) capabilities. There is an 802.11n version of Minstrel, but there is no similar implementation of SampleRate.

We implemented SampleRate as outlined in the thesis, but the MadWifi implementation has a few key differences from the thesis. MadWifi use of an EWMA instead of a window has more accurate rate statistics, which will potentially lead to better throughput. We did not have the time to implement this alternative version, but it is worth further examination.

Hari Balakrishnan suggested that we use 802.11 broadcasts to collect our traces, instead of link layer acknowledgments. We would have multiple computers listening at the broadcast address, and recording all received packets. If packets were sent over UDP, each computer's record of which packets it received would allow us to compute the success probability for each packet for each rate. This approach would free us from certain idiosyncrasies of reading data from the driver, and lead to possibly more accurate traces, as well as the ability to test multiple scenarios at once. We were unable to implement this due to a lack of time and inability to acquire compatible hardware.

Finally, we are considering submitting our improvements to the Minstrel algorithm, namely the balanced EWMA, as a kernel patch. Currently our changes implemented in Python, so we would have to port our improvements to C.

9 Conclusion

Minstrel and SampleRate perform similarly. The results suggest that SampleRate tends to perform better, except in very lossy links such as the client being far away from the AP or actively moving. Minproved, our improved version of Minstrel, solidly outperforms both Minstrel and SampleRate.

It seems that the replacement of SampleRate in the Linux kernel may have been hasty, since it performs similarly to Minstrel in many situations and in most situations and is a much simpler algorithm, and thus easier to adapt to changing wireless standards. We are not sure if adjustments to SampleRate can bring its performance to match that of Minproved, however.

Acknowledgments

We would like to thank Jonathan Perry and Hari Balakrishnan for their valuable guidance, as well as Derek Smithies for answering our questions about Minstrel.

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