Environment Effects on 802.11n Physical Layer Transmission Features Relationships

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Abstract

Over the years, wireless routers have achieved better throughput because of physical and MAC layer optimizations like short guard interval, wider channels, multiple-input and multiple-output, and frame aggregation. The emergence of physical layer features has emphasized the need for efficient rate changing algorithms. In 2016, Ali Abedi and Tim Brecht [Ali *et al.*] introduced a novel approach of estimating frame error rates (FER) of one configuration from the FER of another [1]. Their results show that in most scenarios, 5% of total configurations are sufficient to determine FERs of all the configurations. In our work, we perform experiments on devices having varying physical layer features in environments similar to and different from the ones in the original work. Our goal is to verify if "magic" set covers exist in high interference network environments and if there is any similarity in the set covers and their size, obtained from our work and the original work.

1 Introduction and Background

Wireless networks are being used almost everywhere nowadays, from the simple network in one's house, to the complex networks found in places like airports and universities, they all share the same underlying technologies to provide their users with a reliable and fast connection.

In order to achieve better throughput, over the years, wireless routers have seen many technological advances. The IEEE 802.11a was one of the first standards implemented in wireless. Since then, mainstream wireless technologies have progressed through standards like 802.11b, 802.11g, 802.11n and currently to 802.11ac. *Rate configuration* refers to a particular combination of physical layer transmission features such as modulation and coding scheme, channel width, short/long guard interval, and the number of spatial streams. Below, we mention the highest possible throughput, the band used and number of rate configurations in each standard.

- 802.11a - 54 MBit/s, 5 GHz and 8 configurations
- 802.11b - 11 MBit/s, 2.4 GHz and 8 configurations
- 802.11g - 54 MBit/s, 2.4 GHz and 8 configurations
- 802.11n - 600 MBit/s, 2.4/5 GHz and 128 configurations
- 802.11ac - 1300 MBit/s, 2.4/5 GHz and 640 configurations

Since our work is focused on 802.11n physical layer configurations, we will briefly discuss about the features available in it. When compared to the 5 GHz band, the 2.4 GHz bandwidth offers longer range, lower speeds, and has more interference because most of the other wireless networks and devices use the 2.4 Ghz band. Channel bonding is the combination of two adjacent channels within a given frequency band. It is worth mentioning that 40 Mhz channel widths work best in the 5 GHz frequency band. Guard intervals ensure that distinct transmissions do not interfere with each another, or otherwise cause overlapping transmissions. The short guard interval time is 400 nanoseconds, which is half the duration of the long guard interval. Shorter guard interval between transmissions increase throughput, but if it is too short, the amount of transmission interference will increase, and throughput will decrease. On the other hand, if the guard interval is too long, there is increased overhead due to the additional idle time. With spatial stream multiplexing (MIMO), multiple data streams are transmitted at the same time on the same channel, but by different antennas. For example, 3x3 means there exist 3 streams for transmission on the sender that can carry unique data, and 3 streams for reception on the client. Modulation type and coding factor are also responsible for determining physical layer throughput.

Average *frame error rate (FER)*, which is the the average number of frames that are received incorrectly by the receiver divided by the total number of frames sent by the sender, is an important metric in determining which configuration is the best to use to achieve the best possible throughput. Ali *et al.* [1] have suggested that there are relations between different configurations and their corresponding FERs. Exploiting these relations can be helpful in designing a rate adaption algorithm that uses less sampling frequency, to achieve higher throughput. The main contributions of the project are:

1. We reproduce the experiments done by Ali et. al in [1], while using both different devices, and conducting the experiments on different environments.

2. We develop a system that can determine the set covers for both a specific and a set of scenarios. More on that in Section 4.2.

3. We examine the relationships between different configurations and the effects of environment and devices types on these relationships.

The remainder of this document is organized as follows: We review previous related research in Section 2. Section 3 describes the experimental environment and data collection. In section 4, we describe the relations between configurations, and ection 4.2 examines the notion of set covers and we conclude our work in Section 5.

2 Related Work

Minstrel_HT [2] is a rate changing algorithm, which is used in the open-source 802.11n wireless driver, ath9k [3]. and many other wireless chipsets, including the ones used in 802.11ac. Minstrel_HT does a random and exhaustive sampling of all 802.11n feature settings to update the expected throughput and loss rate of each feature setting combination. The configuration which provides the highest expected throughput is chosen for data transmissions. However, if the selected rate has a high frame error rate, then it lowers the rate by reducing the number of streams. The main issue with Minstrel_HT is that sampling every configuration will incur a significant overhead.

Previous work in this field showcase the drawbacks of Minstrel_HT and suggest new rate changing mechanisms [1] [4]. Ali *et al*. [1] propose that relationships may exist between the average frame error rate of different configurations because several physical layer transmission feature combinations share common features. If it is possible to estimate the FER of one configuration from the measured FER of another configuration, algorithms that adapt configurations to changing channel conditions may be faster. In realistic environments, there are many wireless networks and wireless devices present in range of each other, but previous work that tried to introduce efficient rate changing algorithms for 802.11n, like [4], perform their data collection experiments in the 5 GHz band, with controlled interference.

Lito *et al*. [4] suggest a novel adaptation mechanism termed SampleLite that leverages passive Received Signal Strength Indicator (RSSI) measurements on the sender side to identify a very small subset of feature setting combinations to sample for each configuration. Unlike previous open-loop schemes, SampleLite reduces the search space to sample without the use of sub-optimal settings, and differently from typical closed-loop schemes, it relies on RSSI already available at the sender side. However, we believe that sub-optimal settings will provide lower frame error rates in scenarios having high network interference. Experimental results show that SampleLite delivers throughput close to ideal, and provides improvements up to 35% compared to Minstrel HT. It reduces sampling overhead by over 70% on average compared to Minstrel_HT.

There were a few drawbacks in their experimental setup that we would like to point out. All the experiments were conducted during late night hours in 5 GHz band with controlled co-channel and adjacent channel interference, but realistic wireless network environments have many co-existing networks on the same channel frequency and most wireless devices use the 2.4 GHz band. Also, the experiments were run with short guard interval (SGI) disabled and a maximum of 2x2 spatial streams. We point out these aspects because SGI, and 3x3 and 4x4 spatial stream are important features of 802.11n that can provide higher throughput.

3 Data Collection and Analysis

We perform the experiments in two different environments having moderate and high interference. In total, we use four different devices as clients, while they are stationary and in motion. In the mobile experiments, a person holding the client device is walking at a normal pace, within access point's range.

3.1 Experimental Environment

We created two test beds in different locations in a university environment, having high network interference from multiple wireless networks and other network devices. One test bed was within a lab with few cubicles, in a university building; it is the same lab where experiments in the original work were performed. The other test bed was in a lounge, next to a cafeteria, in one of the

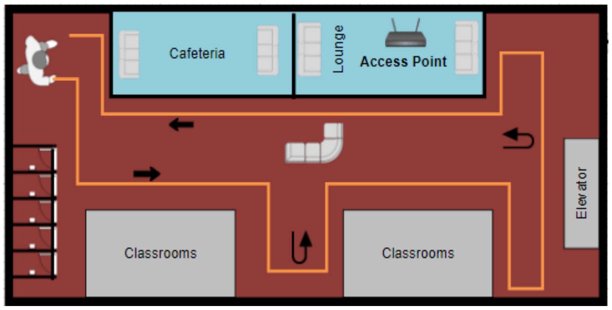

Figure 1: Mobile experiments in the lounge scenario. The orange line indicates path of the mobile device.

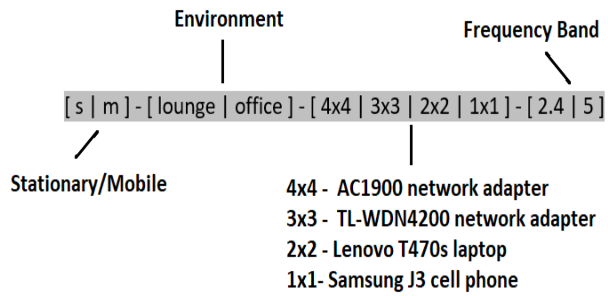

Figure 2: A notation representing characteristics of an experiment.

university buildings. It was more crowded and had students moving around, with almost all of them using cell phones or laptops. In both scenarios, our access point was a TP-Link TL-WDN4800 dual-band wireless N PCI-E adapter, which uses Atheros AR9380 chip-set and supports a maximum of three spatial streams. This device uses the open source Ath9k device driver. For both stationary and mobile experiments, we used the same client devices like network adapters, a laptop and a cellphone. This is a brief overivew of physical layer features of the client devices:

- TP-Link AC1900 network adapter - 2.4/5 GHz band, 20/40 MHz channel, SGI/LGI, 4x4 streams, 128 configurations
- TP-Link TL-WDN4200 network adapter- 2.4/5 GHz band, 20/40 MHz channel, SGI/LGI, 3x3 streams, 96 configurations
- Lenovo T470s laptop - 2.4/5 GHz band, 20/40 MHz channel, SGI/LGI, 2x2 streams, 48 configurations
- Samsung J3 mobile phone- 2.4 GHz, 20 MHz channel, SGI/LGI, 1x1 stream, 16 configurations

In the office environment, no line-of-sight exists between the AP and client during the entire duration of stationary experiments, and for a major duration of the mobile experiments, as the signal is blocked by cubicle partitions. For the stationary experiments in the lounge, the client devices were placed at different locations for each experiment, where either glass or concrete walls obstructed the line-of-sight. A snapshot of the test bed layout for mobile experiments in the lounge environment is shown in Figure 1, and the path followed by the client device is represented by the orange line.

In Figure 2, we introduce a notation to denote the characteristics of an experiment. The order of the notation represents a stationary or mobile experiment, the experimental environment, the device, and frequency band, respectively.

3.2 Collection of Data

Using Iperf [5], we generate UDP data packets that are sent from the access point to the client devices. In each experiment, we record the frame error rate of all packets sent for a duration of 15 minutes. We have access to the modified ath9k driver developed by the authors of [1], which implements a rate configuration selection algorithm that transmits using each configuration in a round-robin fashion. Round-robin mechanism exposes all rate configurations to similar network conditions at any given time and facilitates a fair comparison of FERs of all configurations, this mechanism has proven to be effective in providing fair comparisons in different scenarios [6, 7]. Since we are evaluating only physical layer relationships, MAC layer frame aggregation is disabled to increase the efficiency of the data collection mechanism. Once we have the frame error rates of all configurations for an experiment, we compute the average FER of each configuration over a 10-second window.

4 Analysis of Configurations Relationships

We refer to a specific configuration using the notation that was introduced by the authors of [1]. The notation is described in Figure 3.

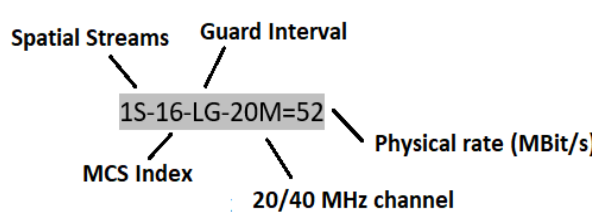

Figure 3: Description for rate configuration notation.

In this section, we first examine one possible way to study the relationships between two configurations, and then use that idea to study how one can estimate all possible configurations using a small set of configurations. Lastly, we study the possibility of finding a set of configurations that is able to estimate all configurations regardless of the environment or devices that are used.

4.1 Estimation Power

To examine the relationships between two different configurations, Ali *et al.* introduced the notion of *Estimation Power (EP)*. To better understand what it means, let us examine the FER between two configurations (namely 1S-I5-LG-20M=52 and 1S-I6-LG-20M=52) as shown in Figure 4. In the plot, a point $p(x,y)$ means that, at some moment in the experiment, the FER of the first configuration was equal to x and the FER for the second configuration was y. These FER values were captured from the m-lounge-4x4-2.4 scenario.

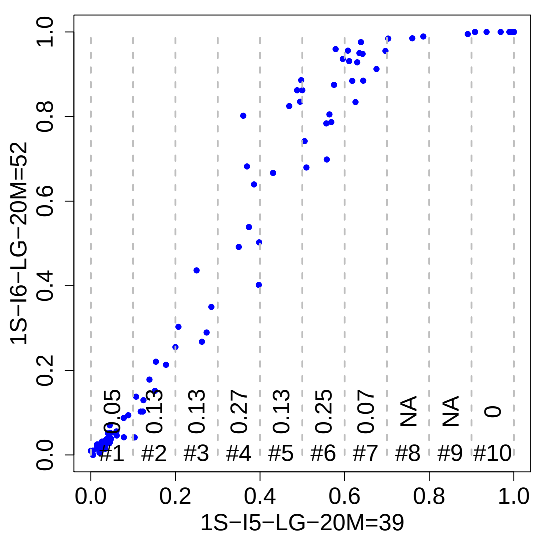

Figure 4: FER scatter plot between two different configurations

To accurately measure the relationship between two configurations, we divide the range of FER into a number of bins (10 in our experiments), then for each bin, we calculate the *dispersion* of points in the vertical dimension. Similar to the previous research, we used the interdecile range to calculate the dispersion. The dispersions for each bin are shown above the bin number, in Figure 4

The *Estimation Power* between two configurations *R1 and R2*, *EP(R1,R2)* is defined as the number of bins with a dispersion less than a threshold, divided by the total number of *defined* bins. A bin is defined if it has enough data points to provide reliable calculations (we used 5 in our experiments). In Figure 4, there are 8 defined bins, and if we use a dispersion threshold of 0.2 then we can calculate $EP(R1,R2) = \frac{6}{8}$, where $R1$ is the $x-axis$ configuration, and $R2$ is the $y-axis$ configuration. If $EP(R1,R2)$ is greater than a specific threshold, we can say that R1 can *estimate* R2.

Although estimation powers of different configurations are useful on their own to provide some insights on how configurations relate to each other, they become even more useful when we look at a group of these together to see how they can estimate the whole space of configurations. This is examined in the next subsection in details.

In our experiments, We used similar settings to those found [1] as to provide fair comparison with their analysis and to show the effects of the environment on the relationships when we preserve everything else. Table 1 summarizes these settings.

Parameter	Value
Number of bins	10
Minimum number of points in a valid bin	5
Bin dispersion threshold	0.2
EP threshold	0.7 & 1.0

Table 1: Parameter settings used in our experiments

4.2 Set covers

To study how strong or weak the relationships between different configuration, we now consider the idea of having a small set of configurations that can estimate all other configurations in a specific scenario. Finding the *smallest* of these is equivalent to the minimum set cover problem, which is proven NP-Hard [1, 8] .

The authors of [1] developed a brute-force approach that allowed them to find set covers of sizes up to 5 configurations in reasonable time. As part of this project, we developed a new program that allows us to find bigger set covers of sizes up to 10. The new algorithm enables us to study the relationships between different configurations in a more detailed manner, and it increases the possibility of finding interesting and useful information that can help us understand more about the relationships between different configurations. Part of our future research would be to reduce this problem into other well known NP-Hard problems, and use the already-well-optimized solvers out there, to find set covers of even larger sizes.

As mentioned before, all our experiments used the settings found in Table 1. Table 3 shows the sizes of the minimum set covers we found for each of the scenarios we conducted in the office environment. We used two EP thresholds (EP th.) in our analysis, 0.7, and the most

EP threshold	Stationary					Mobile				
	4x4 2.4 GHz	4x4 5 GHz	3x3 2.4 GHz	2x2 5 GHz	1x1 2.4 GHz	4x4 2.4 GHz	4x4 5 GHz	3x3 5 GHz	2x2 2.4 GHz	1x1 2.4 GHz
0.7	5	5	4	3	2	2	2	3	1	1
1.0	8	6	≥ 10	6	6	9	7	5	4	3

Table 2: Minimum set covers sizes for lounge experiments

conservative 1.0. Although the office environment is a bit static in the sense that not many people move around with different devices, it still has external interference from other neighboring networks (especially for the 2.4 GHz scenario), and from other computers and devices within the office itself.

EP th.	Stationary			Mobile	
	4x4 2.4 GHz	4x4 5 GHz	2x2 5 GHz	4x4 5 GHz	2x2 5 GHz
0.7	2	3	1	1	1
1.0	3	3	1	1	1

Table 3: Minimum set covers sizes for office experiments

Although the devices we used are different from the ones in [1], we still obtained similar results. This suggests that relationships between different configurations exist regardless of what devices are used. Furthermore, we conducted two other scenarios in which we used a 2x2 MIMO device with a smaller set of available configurations (64). We can see that in all these scenarios, we were able to find very small sized set covers, (≤ 3) even while using the most conservative EP threshold of 1.0.

Table 2 shows the results we obtain, when we analyze the traces from the set of experiments conducted in the lounge. The lounge environment was very crowded with many students going around the area where we were conducting our experiments. Furthermore, the area had devices that interfere with WiFi signals, such as multiple microwaves. We have also considered the two EP thresholds (0.7 and 1) in our analysis. In our 2.4 GHz set of experiments, we used the same channel as the university WiFI, to have as much interference as possible.

Despite all the interference around our experimentation area, we can see from Table 2 that we were able to find small sized set covers (≤ 5) for all scenarios when we used the EP threshold 0.7, and set covers of size (≤ 9) for 9 out of 13 scenarios we experimented on (only 10 of these are shown in the table). This suggests that relationships between configurations are useful even in very crowded environments.

4.3 Super Set covers

In the previous subsection, we studied how a small portion of configurations can be used to estimate all other configurations in the same scenario. The ultimate goal however, would be to find a small set of configurations that can estimate many configurations, regardless of how the environment or the devices under use change. We call the set of configurations that can estimate multiple scenarios a *super set cover (SSC)*.

To find such an SSC for two scenarios, lets donate the set of all the configurations in the first scenario (S_1) as $(R_1,...,R_{96})$ along with their relations, and the set of all configurations in the second scenario (S_2) as $(T_1,...,T_96)$. we define a new scenario that combines both, with a set of configurations $(V_1,...,V_{96})$ in which V_i estimates V_j only if R_i estimates R_j **AND** T_i estimates T_j.

By running the algorithm that finds the minimum set cover on the newly defined scenario, we're guaranteed to find a set cover that can estimates all the configurations in the first scenario and all the configurations in the second scenario, hence it is an SCC for S_1 and S_2. We can extend this idea to find SCCs for larger numbers of scenarios.

Using our code, we were able to find a few SCCs, the most interesting of which might be an SCC of size 10 for the following scenarios: s-office-3x3-2.4, m-lounge-3x3-2.4, s-lounge-3x3-2.4, s-lounge-3x3-5 and m-lounge-3x3-5. Despite the fact that these scenarios are different than each other (some in an office environment while others in a crowded environment, some are stationary while others are mobile and some used 2.4 GHz while others used 5 GHz), and that we were able to find an SCC for them, suggests that the relations between configurations can indeed be used to develop a new rate adaptation algorithm that can use less sampling, while achieving great (if not optimal) throughput.

We were also able to find a small SCC of size 4 for all the scenarios that were done in the office environment using an EP threshold of 0.7, and even when used the most conservative EP threshold of 1, we were able to find an SCC of size 7 for all the office experiments.

More research on this area needs to be conducted as initial results we obtained seem to be very promising.

5 Conclusions

In this paper, we verify the idea that frame error rates of one configuration can estimate the frame error of an another, and that the presence of relationships between different configurations is not restricted neither by the physical layer features of the devices, nor the interference present in the testing environments. We find that in all the 18 scenarios examined, considering an EP threshold of 0.7, the set covers are fairly small (maximum set cover is 5). This means that at most 5 configurations are needed to estimate the FER of all other configurations in most scenarios. It is surprising that these relations hold true in environments with high interference. Furthermore, by examining *super set covers* of different scenarios, we demonstrated that there might be a set of configurations that can estimate many other configurations regardless of the environment or devices being used. This demonstrates, and strengthens, the possibility that relationships between rate configurations can be used to design rate adaptation algorithms that uses fewer sampling rates than those being used currently by most rate adaptation algorithms in commercial routers.

6 Acknowledgments

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