Research Statement

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My research interests are in the areas of wireless networks, computer systems, IoT, and performance evaluation. I have been the lead researcher in projects ranging from designing ultra low-power communication systems for IoT devices to characterizing the performance of modern WiFi networks.

Wireless local area networks are widely used in homes, schools, and many other public places. The growth of the WiFi market is driven by many factors, such as the widespread use of smartphones, IoT devices, and the demand for free public WiFi hotspots. It is anticipated that the next generation of WiFi chipsets (802.11ax) will break the 1 billion annual shipments barrier by 2022. Everyday we rely more and more on wireless networks from fast wireless internet access to low-power wireless connectivity for IoT devices. The main focus of my research has been on pushing the limits of WiFi networks by 1) improving existing networks such as designing a near-optimal frame aggregation algorithm for WiFi networks and 2) enabling new capabilities such as designing a system that enables communication between battery-free IoT sensors and WiFi devices.

1 Battery-Free WiFi-Compatible Communication for IoT Devices

Most recently, I designed WiTAG [6], a battery-free backscatter communication system for transferring sensors’ data (e.g., a temperature sensor) to a WiFi device. A prototype of WiTAG is shown in Figure 1. Backscatter systems are very attractive as a means of communication for wireless sensors in applications ranging from implantable body sensors to farm monitoring. This is because of their low cost, small form factor and ease of maintenance since they do not require batteries. WiFi-based backscatter systems provide the potential to deliver battery-free sensors (tags) which can transmit data using a WiFi network. Existing backscatter systems have several problems which make them impractical to deploy and operate using existing WiFi networks. First, they require software or hardware modifications to WiFi access points and devices. Second, they do not work with WiFi networks that use a security protocol such as WPA. Third, they interfere with existing WiFi communication because they reflect their signal to another channel without implementing channel sensing.

In designing WiTAG, I took a radically different approach from previous work by leveraging the use of A-MPDUs (frame aggregation) to enable backscatter communication. WiTAG works with the latest WiFi standards (802.11n and ac), does not require any modification to access points, and does not interfere with existing WiFi communication (since it does not use a second channel). Most importantly, because WiTAG selectively alters the wireless channel to communicate data by leveraging MAC-layer frame aggregation (rather than modifying PHY-layer symbols) it is compatible with both open and encrypted WiFi networks. The evaluation of our prototype system shows that WiTAG can achieve data rates of 40 Kbps rendering it an excellent choice for battery-free communication for IoT devices.

2 Practical, Near-Optimal Frame Aggregation for 802.11 Networks

MAC-layer frame aggregation has significantly improved the efficiency of IEEE 802.11n and ac networks by placing multiple MAC-layer data units in a large PHY-layer frame. However, the 802.11 standard does not specify the frame aggregation algorithm that determines how many subframes should be aggregated at any point in time. An 802.11 aggregated frame is called an Aggregated MAC Protocol Data Unit (or A-MPDU). In theory, A-MPDUs amortize overheads over more bits and therefore increase throughput. However in practice, throughput can be negatively impacted if too many frames are aggregated because some of them may fail. Determining the optimal number of
subframes is challenging because error rates can be higher in the later part of the A-MPDU which change with factors such as mobility, speed and transmission rate. Additionally, there are dependencies between consecutive A-MPDUs due to the retransmission of the failed subframes.

I have developed a model of A-MPDU frame aggregation and used it to design a statistically optimal algorithm [under review]. However, this algorithm requires a priori knowledge of subframe error rates. To overcome this limitation, I have developed a standard compliant, practical, near-optimal frame aggregation algorithm that does not rely on such information. Instead this algorithm estimates the expected subframe delivery ratios to determine the number of frames to aggregate and approximates the statistically optimal algorithm. We have evaluated the performance of the proposed algorithm with that of a statistically optimal algorithm under a variety scenarios (S1 to S7) with different channel conditions and WiFi devices. Figure 2 shows that the performance of our algorithm is very close to the statistically optimal algorithm across all scenarios. Specifically the average throughput of our algorithm is within 97% of the average throughput of the statistically optimal algorithm. Our practical algorithm can be easily implemented on different types of access points to improve per-client and overall network throughput.

3 Characterization of 802.11 Networks

3.1 Bitrates in Modern 802.11 Networks

In the past 20 years, several IEEE 802.11 standards have been introduced for WLANs. The speed of wireless links in these networks has increased from 1 Mbps to more than 1 Gbps. Since 802.11 standards are backwards compatible, todays WiFi networks may consist of a variety of client devices ranging from legacy 802.11a/b/g to modern 802.11n/ac devices. The drawback of backwards compatibility is that devices with lower bitrates can potentially reduce throughput for higher bitrate devices. In addition, the throughput of WiFi networks is affected by many other factors including the density of devices on the same wireless channel and the time-varying channel conditions that can lead to errors in wireless links. Consequently, the quality of experience can differ considerably from one device to another, even in the same WLAN. As a result, very little is known about the maximum achievable bitrate of WiFi links in commonly used home and office settings. Knowing information about device capabilities is valuable to ISPs and service providers that deliver content to end users connected to the Internet via WiFi networks. For example, for a video streaming service, it is difficult to find root causes of performance issues because it is not clear if the problem is in the ISP to modem connection or the users local wireless network.

In a recent joint project with Google, I led a study [7] that characterizes bitrates used by WiFi devices and their capabilities by examining a large data set collected from modern commercial Google access points. We obtained data from 448 Google Wifi and Google OnHub access points with 2,975 clients. We characterize modern networks comprised of 802.11ac access points which are backwards compatible with legacy protocols. We also examine how close the physical-layer bitrates are to their maximum as a first step in understanding how to improve the bitrates used in practice. We find that about 80% of the client devices operate within 20% of their maximum. However, the bitrates of the remaining devices can be very far from the maximum, which could significantly reduce the throughput of high-bitrate devices. In this project, we analyzed a relatively small data set compared to what we hope to study in the future. We expect to get data from Google for many more devices for longer periods of time. In addition, we hope to study the throughput of WiFi networks by considering error rates and the competition to access the wireless channel.
3.2 Relationships Between 802.11 Numerous Transmission Rates

As a Ph.D. student, I led a project that is concerned with characterizing relationships between 802.11 transmission rates. This project can have a big impact on the design of 802.11 optimization algorithms, WiFi access points, devices, and future 802.11 standards. Our findings can significantly improve the throughput of WiFi networks, greatly enhancing user experience. In a joint project with the Google, we are currently utilizing some of our findings to optimize their WiFi products.

The 802.11g standard supports 8 transmission rates that correspond to different modulation and coding schemes. In the 802.11n and subsequent standards, other transmission features with selectable configurations such as guard interval and channel width were introduced. Different combinations of these transmission features create many transmission rates. Table 1 shows the rapid growth in the number of transmission rates in the 802.11 standard. The 802.11ax standard, which is going to be released publicly in 2019, supports up to 1,152 transmission rates. Some optimization algorithms, such as rate adaptation algorithms, try to maximize throughput by trying to find the best combination of transmission features. The larger the number of rates, the more difficult it becomes to choose the best rate.

<table>
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<tr>
<th>Standard</th>
<th>MCS</th>
<th>Guard Intervals</th>
<th>Channel Width</th>
<th>Spatial Streams</th>
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<td>3</td>
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<td>8</td>
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<td>2019</td>
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</table>

Table 1: The rapid growth in the number of transmission rates in 802.11

We have characterized 802.11n networks [2] with the purpose of finding relationships between transmission rates in order to reduce the size of the search space for optimization algorithms. We have found that strong relationships exist between most transmission rates even under highly-variable channel conditions, including those that are affected by WiFi and non-WiFi interference and mobility. As a result of determining these relationships, optimization algorithms can probe a small subset of all transmission rates and infer the error rates of other transmission rates instead of probing them. We have shown that a rate adaptation algorithm that implements a simple heuristic that takes advantage of the existing relationships can improve throughput by up to 28% compared to the default version.

4 Performance Evaluation Methodologies for WiFi Networks

4.1 Empirical Evaluations

Wireless channels change over time due to the movements of the sender, receiver, or nearby objects (due to large-scale and small-scale fading). In addition, interference from WiFi and non-WiFi devices in the shared spectrum increases fluctuations in the attainable throughput in 802.11 networks. A fair and valid empirical comparison of two or more competing algorithms or systems that depend on 802.11 networks can be extremely challenging due to changes in the channel quality. When a channel changes over time, it is not clear if an observed difference in the performance of two competing alternatives is due to the variable channel conditions or differences in those alternatives.

We have examined different existing methodologies for conducting experiments [4] to compare the performance of systems that use 802.11n MIMO networks. We have shown that commonly used techniques for comparing the performance of different alternatives are flawed, even in highly controlled environments that are free from interference from other WiFi and non-WiFi devices. We have found that even running the experiments multiple times to obtain an average with confidence intervals can produce misleading results. We have proposed and evaluated the Randomized Multiple Interleaved Trials (RMIT) methodology, which provides repeatable results and can be used to distinguish differences in performance, even with highly-variable channel conditions. We have shown that the empirical evaluation of 802.11 networks should be done with extreme care and have provided some guidelines for researchers to consider when conducting experiments. I believe that the RMIT methodology must be used for all experiments that involve comparing two or more competing alternatives.
4.2 Trace-Based Evaluation

I have designed novel trace-based frameworks, namely T-RATE [1] and T-SIMn [5, 3], for the performance evaluation of 802.11g and 802.11n networks, respectively. The main goal of these frameworks is to achieve repeatability and realism when evaluating the performance of 802.11 networks. To achieve this goal, T-RATE and T-SIMn record information related to channel conditions that affect throughput in a trace and then use this trace to simulate different 802.11n optimization algorithms such as link adaptation and frame aggregation (as shown in Figure 3). As a result, our trace-based simulators can be used to achieve repeatability by using an identical trace to evaluate different algorithms. In addition, these simulators achieve realism since they rely on traces that are subject to and include information related to actual channel conditions rather than using wireless channel models, which are known to lack realism. Through extensive evaluations, we have shown that our trace-based simulators obtain realistic and high fidelity results.

![Figure 3: Overview of the trace-based framework](image)

I believe that these trace-based simulation frameworks should become the new standard to be used when comparing the performance of competing alternatives. I expect that these frameworks will be suitable for easily and fairly comparing systems that depend on WiFi networks and algorithms that must be optimized for different and varying 802.11 channel conditions which are challenging to evaluate experimentally. Our vision is to create a large repository of traces collected in a wide variety of scenarios, so that researcher all over the world can contribute to and use these traces. When a sufficiently large repository is created, researchers can evaluate their new algorithms or systems in a variety of scenarios without having to conduct empirical evaluations. In addition, they can quickly and easily compare the performance of their new algorithm or system with many previously evaluated systems.

5 Future Directions

5.1 Ultra-Low-Power Communication Systems for IoT Devices

It is estimated that the number of IoT devices shipped annually will pass 21 Billion in 2025. Over 15 Billion of these devices are expected to connect to the Internet via Wireless Local Area Networks (WLAN) or Wireless Personal Area Networks (WPAN). Today’s IoT devices rely on batteries to transmit their data to a base station. Since wireless transmission is power hungry, batteries must be replaced every few years in the best case. Changing batteries of many IoT devices increases the overhead of maintaining these devices. Ideally if the power consumption is reduced enough, IoT devices can operate by harvesting RF energy or utilizing a small solar panel. Eliminating the battery makes IoT devices almost maintenance free. I plan to study ultra-low-power communication systems for the next generation of IoT device.

5.2 Further Characterization Studies

Our recent characterization study [2] has opened up many avenues for future work. One such avenue is to more thoroughly characterize relationships and thereby improve our understanding of how they can be utilized in more practical situations. My vision is that an access point (AP) would obtain information about the relationships between different rates (possibly through a calibration phase) and then use those relationships to estimate the FERs of other...
rates without having to actually sample them. As a result, the AP could optimize the selection of transmission rates to achieve higher throughput. Our preliminary investigations, using only a few devices over relatively short periods of time, have shown some of the potential of this approach. However, new research is required to better understand how relationships can be used to develop practical algorithms that work with the wide variety of devices available in the marketplace. I intend to study the robustness of relationships across different devices and over time.

Another research avenue I would like to investigate is the effectiveness of numerous transmission rates in 802.11 networks. The increasing trend of the number of transmission rates in the 802.11 standards motivates the need to study the cost-benefit analysis of supporting many transmission rates. In other words, how many transmission rates are actually required: can 802.11 networks perform as well or even better with fewer transmission rates?

### 5.3 Millimeter Wave (mmWave) Communication Systems for IoT Devices

The proliferation of IoT devices has increased the strain on today’s WiFi and cellular networks. Millimeter wave (mmWave) frequency bands address this problem by offering multi-GHz of unlicensed bandwidth. Recently there has been much interest in performing research on millimeter wave communications. Prior work utilizes this technology to enable Gbps wireless links. However, existing mmWave radios are costly and have high power consumption rendering them unsuitable for IoT sensors. I plan to explore this research avenue to bring mmWave technology to IoT devices to offload the congested 2.4 and 5 GHz bands onto mmWave ISM bands.

### References


