Unifying the Configuration of Wireless Networks with Effective SNR

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Abstract

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A long lead in for an abstract that'd be ok but leaves you too little room to set up what you did

Wireless networking technology has become fast, cheap, and low power, and is now being adopted in consumer electronics such as smartphones, printers, speakers, video cameras, televisions, and DVD players. Because of its rapid adoption in a diverse set of devices, Wi-Fi is poised at the heart of the next networking revolution: the combining of these diverse consumer devices to build rich applications that leverage each device's unique features.

Despite these great technology, standardization, and adoption trends, one major factor challenges th~~ese~~ future wireless applications: ~~Realizing Wi-Fi's significant potential~~ for sp~~eed, capacity, and reliability~~ requires ~~that the network be configured to support~~ the set of ~~devices in the network and how they~~ are used. ~~The issue is that~~ the underlying Wi-Fi technologies and network architectures have become rather complex, and how to configure and control them has become a significant decision problem without a simple, comprehensive solution. configuration

The standard algorithms used to configure networks take a "try-it-and-see" approach to choosing parameters. These approaches react slowly to changing ~~channels and~~ environmental conditions or device mobility they generally cannot control multiple interacting parameters—such as wireless bitrate and network topology—concurrently. ~~But~~ These limitations a~~re precisely~~ ~~located~~ w~~here wireless applications are heading~~ will be even more important in the future, as devices are used in tandem and used while mobile. ~~Instead~~, Wi-Fi systems need a better way to optimize the operating point of a link and of the network, ~~that~~ to incorporate key configuration factors and ~~can~~ to rapidly respond to changing conditions.

In this ~~thesis~~, I develop a comprehensive way to configure wireless networks using low-level RF physical-layer(?) channel measurements. ~~with~~ I devise a simple but powerful model that can predict the performance of every operating point in the entire configuration space. This provides a simple, fast, accurate way to configure the network and completely replaces a broad class of complex configuration algorithms.

"try it and see?"

previous ~~approaches~~ techniques.

By using a single channel measurement and extrapolating over a wide configuration space, ~~my~~ approach is considerably more practical than ~~probing everything~~. By using low-level RF information, my approach is considerably more accurate than approaches that only use ~~high-level~~ aggregate signal strength information. Thus my approach represents a great tradeoff between these two extremes, maintaining the flexibility and accuracy of probe-based approaches while achieving the simplicity and low overhead of the latter.

To evaluate my work, I implement my model using a state-of-the-art commodity 802.11n wireless device and evaluate its use in a variety of applications over real links. I find that when my model is integrated into wireless network configuration algorithms, the choices made lead to good performance in practice, and that my techniques can solve joint parameter optimization problems. Together, these show that my model unifies the decision-making components of wireless network configuration algorithms into a single comprehensive framework that is practical and provides good performance.

You don't set this tradeoff up, so it's kind of mush.
Need to better explain that there are two previous approaches - ones using SSI (that don't work) & ones using try + see (that do but are slow)
And yours is different + better than both

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DEDICATION

here goes dedication

Chapter 1
INTRODUCTION

Wireless local area networks are used today in locations such as cafés, shopping malls, corporate offices, and homes to connect devices wirelessly at high rates over a short range. The dominant technology for these networks is Wi-Fi (IEEE 802.11 [43]), which emerged in 1997 as a way to connect computers wirelessly to a nearby (within 100 m) Internet "access point" at rates up to 2 Mbps.

The past fifteen years have seen Wi-Fi technology improve dramatically, and today's commercial Wi-Fi devices come at low cost, have a small physical footprint, and offer dramatically increased speeds (up to 600 Mbps in IEEE 802.11n [44]). Wi-Fi is no longer limited to traditional computing devices such as laptop and desktop computers, but is also being adopted by consumer electronics such as smartphones, printers, speakers, video cameras, televisions, and DVD players. An ABI Research report [1] forecast that more than half of the 1 billion Wi-Fi chipsets shipped in 2011 would be used in consumer electronics.

Because of its rapid adoption in a diverse set of devices, Wi-Fi is poised at the heart of the next networking revolution: the combining of these diverse consumer devices to build rich applications that leverage each device's unique features. This stands in sharp contrast with today's access point model, in which devices only use wireless connectivity to interact with the Internet at large, and the protocols used in Wi-Fi networks are completely centralized and structured around this goal. In order to support this shift away from the access point model, a new protocol called Wi-Fi Direct [121] was standardized in late 2010 that enables Wi-Fi devices to form networks that better match their applications. Wi-Fi Direct has seen great uptake: a second ABI Research study [2], conducted in late 2011, forecast a 50% annual growth rate for Wi-Fi Direct support and predicted that there will be 2 billion Wi-Fi Direct-enabled devices by 2016.

Despite these great technology, standardization, and adoption trends, one major factor challenges these future rich wireless applications. Realizing a Wi-Fi network's significant potential for speed, capacity, and reliability requires that the network be configured to support the set of devices in the network and the applications that users wish to run. The issue is that the *underlying Wi-Fi technologies and network architectures have become rather complex, and how to configure and control them has become a significant decision problem without a simple, comprehensive solution.*

Consider rate selection, the goal of picking the fastest way to transmit data on a wireless link. In the first version of 802.11 released in 1997, the rate selection task consisted of choosing between two modulations to transmit data. Early algorithms just tried both rates and picked the better one. This trend held through 802.11b and 802.11a/g, because with up to 12 different rates to choose from, "try-it-and see" algorithms that probed all options, though not perfect, generally sufficed. But three tends in Wi-Fi links today make this task much more challenging.

First, modern 802.11n devices that support fast rates now rely on the ability to send with multiple antennas, thereby adding another dimension to the search space and growing the number of rates into the hundreds. Second, the nature of new algorithms for device-to-device networks like Wi-Fi Direct require extensive coordination between pairs and sets of devices in a network, growing the search space exponentially. Finally, wireless devices are increasingly used while mobile, both while walking indoors and in vehicles. This combination of factors means that algorithms to configure the network need to respond faster to match changing channels, while simultaneously choosing from among more possibilities. This problem goes beyond the mere task of rate selection.

An example configuration problem for a device-to-device network would be choosing a multihop path between a source and destination device, possibly using intermediate devices as relays. One step in solving this problem involves assessing the performance achievable on each potential link, taking into account the effect of using different rates, number and sets of antennas, and even the quality of using the best among multiple operating channels. Past solutions to each of these *subproblems* tend to assume away most dimensions of the configuration space ~~to be practical~~—e.g., by assuming homogeneous single-antenna nodes and fixing the entire network to a single bitrate, frequency, and transmit power, ~~so that~~ the system need only probe packet delivery for a single rate.

~~But~~ To get good performance in future wireless networks we need to solve all these problems, often at the same time. ~~Using past solutions as evidence indicates that~~ The probe-based algorithms used until now ~~may~~ will not scale to handle these future systems. Instead, Wi-Fi systems need a better way to optimize the operating point of a link and of the network that incorporates all of these key configuration factors and can rapidly respond to changing conditions. Here's where you should talk about using SSI – & why that does not work.

In this thesis, I develop a practical solution to this problem. In particular, I develop a comprehensive way to inform these complex decision problems using low-level RF channel measurements. ~~with~~ I devise a simple but powerful model that can predict ~~the performance~~ of every operating point in the entire configuration space. By using a single channel measurement and extrapolating over a wide configuration space, my approach is considerably

Not really one, 3A?

avoid undefined jargon –

Figure 1.1: A single Wi-Fi link, in which the transmitter T sends data to the receiver R. No other wireless devices are present.

more practical than probing everything. By using low-level RF information, my approach is considerably more accurate than approaches that only use high-level signal strength information. Thus my approach represents a great tradeoff between these two extremes, maintaining the flexibility and accuracy of probe-based approaches while achieving the simplicity and low overhead of the latter.

see abstract comment - applies here.

In the rest of this chapter, I first explain the problem in further detail. I then present my hypothesis and explain my approach to solving this problem. I conclude this chapter by discussing the contributions of my work and the organization of the rest of this thesis.

1.1 The Problem

As stated above, ~~the~~ a major challenge for Wi-Fi networks today is finding a good configuration in a changing world. To introduce the problem, I present the main configuration problems in these systems, and briefly explain why today's Wi-Fi solutions are insufficient.

1.1.1 Configuring a Single Link

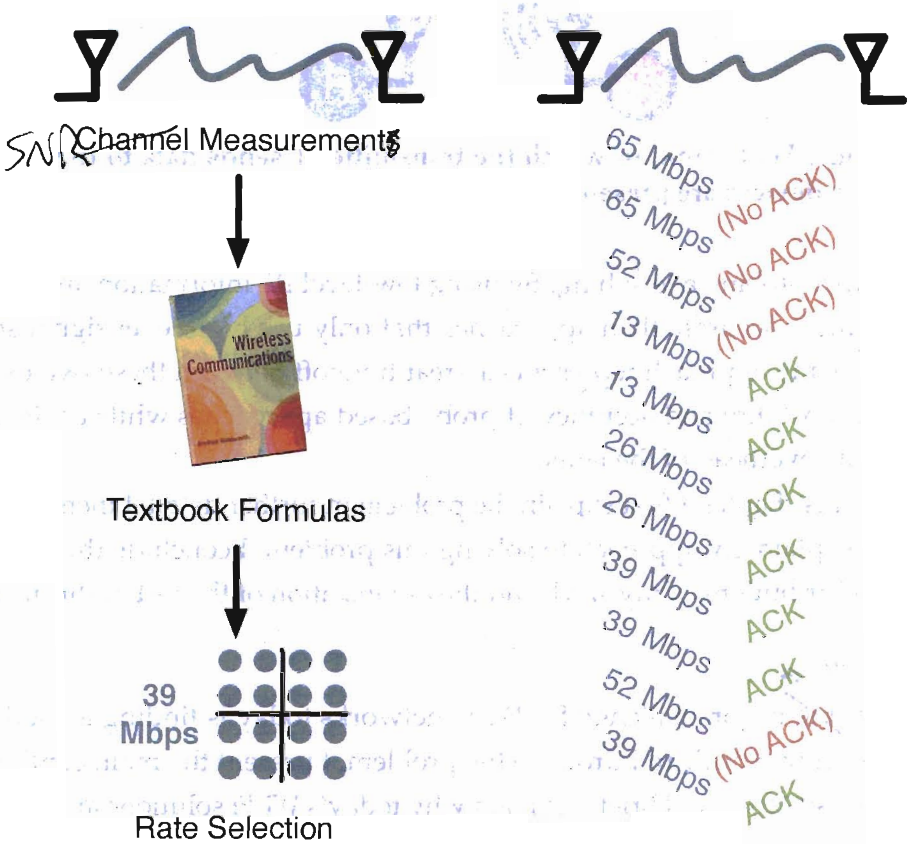
The most basic wireless network is a single link (Figure 1.1), in which a transmitter sends data to one receiver, with no other devices present. In this section, I will show that configuring a wireless to work well ~~link~~ involves choosing the right operating point in a large multi-dimensional space.

Perhaps the simplest configuration goal for a wireless link is *rate selection*: the transmitter should send its data to the receiver using the fastest rate at which it will be successfully received. Sending data more slowly ~~would be less efficient because~~ obviously means the transmission ~~would~~ take longer ~~and use more power than necessary~~.[1] At the same time, sending faster would be inefficient because the data would not be received, wasting all the airtime and power consumed during the transmission.

In principle, selecting a rate for a wireless link should be trivial according to the laws of communications theory. Whether a transmission sent with a particular modulation and coding scheme is received is determined entirely by the amount of power delivered to the receiver and the noise level present. This limit is quantified in the *signal-to-noise ratio*, or

[1]Unless the transmitter reduced its radiated power, but this is typically not done in practice.

I'd avoid this → it's not needed, & it undermines later discussion where power is variable



(a) The theoretical approach to rate selection based on SNR measurements. **(b) The probe-based approach to rate selection, ~~used in practice~~.**

Figure 1.2: Approaches to rate selection.

SNR. The transmitter need only measure the channel SNR and apply textbook formulas that can compute the error rates of particular modulations. The fastest rate can then be easily selected. This approach is described in Figure 1.2(a).

In practice, this approach has never worked for Wi-Fi links. The 802.11 standard defines a channel metric related to the SNR called the Receive Signal Strength Indicator, or RSSI, that captures the total amount of power in the channel, ~~and~~ in most chipsets the is ~~indeed~~ a direct measure of the SNR. However, Wi-Fi systems have never used RSSI as more than a coarse indicator of expected performance. There have simply been too many ways in which the observed measurements and actual performance fail to match the predictions of theory. For example, hardware estimates of RSSI can be mis-calibrated, the wireless channel can vary over packet reception, and it can be corrupted by interference; all of these are known to be issues in practice [18, 54, 94].

Since rate selection based on RSSI has never worked for Wi-Fi, practical systems use *rate* *adaptation* algorithms instead [15, 108, 122]. These algorithms, exemplified by Figure 1.2(b), are guided search schemes that simply test individual rates to see how well they work. When the loss rate is too high, a lower rate is used; otherwise a higher rate is tested. This approach works well for slowly varying channels and simple links, since the best setting will soon be found.

However, remember the Wi-Fi trends discussed earlier: the transmit configuration of a single Wi-Fi link now includes not just rate, but additional dimensions that take into account the use of multiple antennas or channel widths, and these devices are increasingly being used while mobile. Thus algorithms to configure the rates of these links need to respond faster to match changing channel~~s~~ conditions, while simultaneously choosing from among more possibilities. As a result, rate adaptation algorithms are ~~getting~~ becoming less efficient ~~as these systems change~~ over time.

evidence? citation?

Thus far, I have described the challenges inherent to choosing an efficient rate to send data on a wireless link. On its own, this is a hard problem, but in addition, I note that rate is only one of many parameters to optimize for a Wi-Fi link. For instance, a transmitter may want to trim excess transmit power to both save energy and reduce interference at nearby receivers. Or a sender might improve a link by selecting a different subset of its transmit antennas, or by applying beamforming techniques to better match the signal to the radio channel. Finally, note that these parameters are not generally independent—changing any one of them can affect the best operating point for another. For instance, switching the operating frequency (of which there are often 10 to 20 options) can dramatically change the RF channel, and this in turn can affect which transmit antennas provide the best link, and how the transmitted signal should be shaped for maximum performance. All of these factors contribute to determining the best way to configure a link.

but you said they don't do this

It's not clear exactly what are the parameters. - provide a list?

In practice, the solution taken by hardware/driver manufacturers today is to simply ignore most of these dimensions. For instance, only Intel's `iwlwifi` driver, out of all the 802.11n drivers in the Linux kernel driver, adapts the transmit antenna set in an online manner. Similarly, few access points and no clients adjust transmit power for ongoing links, instead opting to transmit at the maximum power ~~and guarantee the best link~~. The solutions work well enough for wireless access point networks, mostly due to the simple way in which links are used today. Still, these solutions are inefficient for a single link—and in the next section, we will see that the problem gets even more complicated when performing network-level configuration of multiple devices that operate in multiple links.

Is that a parameter?

1.1.2 *Configuring a Network of Devices*

In this section, I will illustrate how a network of devices has a significantly larger configuration space than a single link. I frame this discussion using the examples in Figure 1.3, which

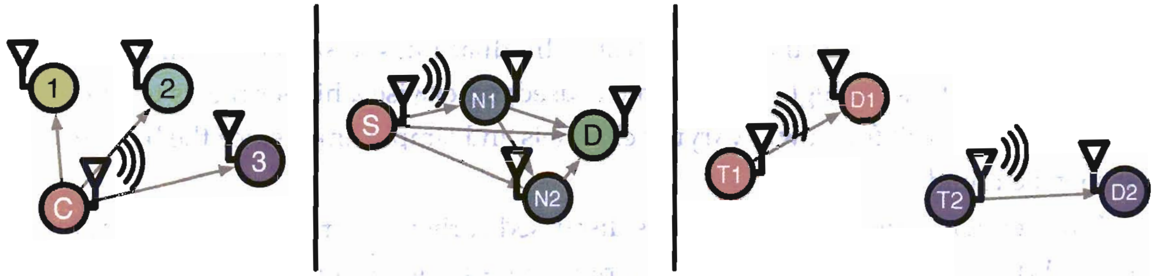


Figure 1.3: The three key configuration problems in multi-device networks. ***Left:*** **access point selection.** ***Center:*** **Multi-hop mesh routing.** ***Right:*** **Spatial reuse.**

represent the three key network-level configuration problems that dense wireless networks like Wi-Fi Direct will have to solve to ~~build rich~~ support device-to-device applications. Depending on the problem being solved, these configuration problems can have increased complexity that is linear in the number of devices (AP selection), quadratic (Multi-hop routing), or even exponential (Spatial reuse).

Access Point Selection

In Figure 1.3, on the left, the client C wishes to join the network offered by the access points AP_1, AP_2, and AP_3. The *access point selection* problem is simple: the client should connect to the access point that provides the link with the best rate. But in order to choose correctly, the client must accurately evaluate the rate offered by each access point. This in turn means that the client must have a way to assess its rate to each access point ~~rapidly~~, i.e., a solution to the rate selection problem described above. Testing all access points using a rate adaptation-like approach would take too long and would take airtime away from ongoing connections. In practice clients simply connect the access point with the highest SNR. This heuristic approach provides only an approximation to the optimal solution and would benefit from a better way to predict performance over measured wireless channels.

~~Since there~~ ~~are often~~ mention security issues ... the APs client ... the same organization? ... may ~~...~~ ~~... support~~

Multi-hop Mesh Routing

In Figure 1.3, in the middle, the source S wishes to send data to the destination D, and nodes N_1 and N_2 are also present in the network. The *multi-hop routing* problem is to choose the best path through the network by which to deliver data from S to D. In this case, many paths are available, such as the direct path S–D, the one-hop paths S–N_1–D and S–N_2–D, and finally S–N_1–N_2–D. To evaluate the different paths, we need to know the rate available on each hop, which in this case would require knowing the rates of six different links. Once again, measuring the ~~ground~~ truth rate of each link by testing each configuration would ~~likely~~ take too long, and it would add considerable overhead to the network.

Practical work in this area primarily takes one of two approaches. Most of the wireless cite cite

mesh research in the past decade avoided this problem by simply ignoring many of the dimensions of the configuration space. These papers not only used single antenna systems at fixed transmit powers, but also typically fixed the entire network to a single rate. The alternative approach, taken by a few recent papers, has been to collect~~ed~~ statistics about packet delivery between all pairs of nodes for different rates, and estimate the rate from the measured SNR for links without sufficient statistics. These recent works have exclusively handled single-antenna 802.11a/b/g networks, and ~~would~~ likely be forced to rely on SNR-based rate predictions if the underlying links used ~~802.11n instead~~.
multiple antennas (as in 802.11n).

Spatial Reuse

The third example, shown in Figure 1.3, is the *spatial reuse* problem. Here, two independent links both wish to communicate at the same time and in the same frequency, and need to share the wireless medium. If the links ~~share the medium, for example~~ each using half the airtime, then each gets half of the rate as if they were operating alone. In certain situations, depending on the placement of the four devices and the amount of interference between the

can be improved by

Devices ~~links~~, i~~t may provide more tota~~l throughput ~~for the links to~~ send concurrently, each using all of the airtime but maybe using a slightly lower rate.

Once again, deciding which of these two possibilities is better requires the system to predict the rate on multiple different links. In this case, the rate needs to be predicted not only for each link in isolation, but also for every possible pair of configurations of the links. In this case, and unlike the prior two problems, the size of the resulting configuration space is the product of the sizes of the space of each individual link. As a result, practical works on spatial reuse for Wi-Fi [105, 120] have simply fixed the entire network to a single rate during experiments.

1.1.3 Summary

future

In this section, I first showed that the configuration problems for a single link have grown dramatically with the switch to 802.11n technology, and then presented the three key network-level configuration problems for Wi-Fi ~~Direct-like~~ networks and explained why

for networks

config problem ~~their solution space~~ is even ~~larger~~ than for a single link.

a bigger issue will

~~The main conclusion from this section is that~~ network configuration algorithms have to deal with increasingly large search spaces as wireless technology and architectures improves, To find good operating points if devices are mobile, we will need to search these large spaces quickly. ~~Given the assumptions made by prior works to make solving subproblems practical~~, the heuristic and adaptation-based approaches used ~~in the simple network problems solved~~ today will ~~may~~ not scale to these bigger problems. Instead, what we need is a way to accurately and rapidly assess the quality of links for all the factors mentioned in Section 1.1.1, and use this process to solve joint optimization problems such as those described in Section 1.1.2.

I think you need one more section here
→ Approach - where you describe the previous work in eff SNR, so that the reader can clearly understand what you did vs. what's in the past.

1.2 Hypothesis and Approach

But this already works for 11a → so we know it's true AND you didn't show it is true for all possible future networks, so need to be more precise

My hypothesis is that *it is possible to unify the decision-making components of wireless network configuration algorithms into a single comprehensive framework that is practical and provides good performance.* for MIMO device-device networks.

To unify decisions about wireless networks, I present a model for wireless links, based on the concept of Effective SNR ~~[78]~~, which can make predictions about packet delivery for a wide space of operating points. These predictions can be used for rate selection, because they will indicate the fastest rate to use, but also support concurrent adjustment of factors such as antenna selection, spatial streams, and transmit power level, in order to cover the full problem space described above.

My model is practical. The measurement and decision procedure has low overhead, with little information sharing required in order to enable application decisions. As a result the network can rapidly respond to varying wireless channels. The model is designed to integrate into modern wireless systems, including the practical implementation aspects of real hardware. I prototype my model in the context of 802.11n using commodity wireless devices.

Finally, my model can make accurately predictions rapidly for the entire search space described above, and hence provides good performance in practice. My thesis includes an in-depth evaluation of my model in the context of many wireless link and network applications.

1.2.1 Approach

To understand how this will work, Figure 1.4 presents a pictorial summary of my approach. This approach is closely related to the "theoretical approach" presented in Figure 1.2(a), with a few key differences.

First, a client will measure the *Channel State Information (CSI)* for a wireless link. The CSI is a fine-grained measurement that can capture details at the levels of frequency-selective fading (to understand performance under OFDM) and independent spatial paths (to understand performance when using MIMO). I noted earlier that Packet SNR has never been used as an accurate predictor of packet delivery for Wi-Fi networks, because it does not capture enough information about the wireless channel; I will present experimental data that confirms this result in ~~a succeeding chapter~~ Chap X. In contrast, my thesis will show that the CSI ~~provides~~ is fine-grained enough ~~information~~ to be useful.

The second step uses the main contribution of my thesis: *a practical Effective SNR-based model for wireless packet delivery*. My model uses the measured CSI as input, and incorporates textbook algorithms, ideas from communications theory, as well as some implementation-specific details to handle a wide variety of channels, hardware devices, and applications. At

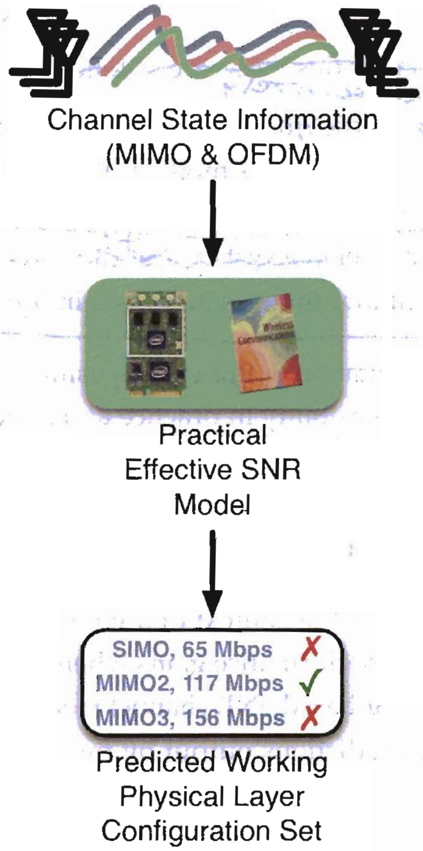


Figure 1.4: An Effective SNR-based approach to making application decisions in 802.11n networks.

the core of my model is the notion of *Effective* E_b/N_0,[2] described in a seminal 1998 paper by Nanda and Rege [78]. In this thesis, I build a practical Effective SNR-based model that uses CSI measurements of the and makes accurate predictions about packet delivery.

Finally, the output of the model is a predicted *set of working physical layer configurations*. For each physical layer configuration in the application space—which can span the choice of modulation, coding scheme, transmit or receive antenna set, and more—the model predicts whether that configuration is likely to deliver packets reliably. The application can then choose among the working configurations in a way that optimizes its objective function. My thesis includes a detailed description of how my model can be used to solve general classes of wireless network configuration problems, and comprehensive evaluations for the key applications that arise in device-to-device networks.

[2]In electrical engineering literature, E_b denotes the energy of a bit and N_0 denotes the noise floor, so E_b/N_0 is the signal-to-noise ratio of a single bit. In the context of 802.11, in which SNR is derived from RSSI, we use a slightly different definition of SNR that is not normalized by the number of bits.

if you move before approach statement thesis statement → this follows thesis stm.

1.3 Contributions

~~To summarize, the contributions of this thesis are as follows~~:

not just a model — one that works!

- ~~First~~, I develop a model ~~to~~ that accurately predict the error performance of different transmitter configurations on the wireless channel. This model is flexible to support a wide variety of transmitter ~~and~~ receiver device capabilities, device implementations, and applications. I ~~also~~ show how ~~detail~~ how to use this model ~~in a system that~~ to ~~can~~ solve a large number and variety of configuration problems similar to those described in Section 1.1.

  ~~own bullet~~ ~~Second~~

- Third ~~Second~~, I present an implementation of ~~this system~~ using a commodity 802.11n wireless device that demonstrates its feasibility in practice and handles the practical considerations of operation over real links using real, non-ideal hardware. This includes a detailed experimental evaluation of my system that shows that this model accurately predicts packet delivery over real 802.11n wireless links in practice.

  this is just the ~~model~~ link model

- Fourth ~~Third~~, I evaluate this system in the context of a wide variety of 802.11n applications, and quantify the application performance gains when using my Effective SNR metric over versions that use the RSSI-based SNR channel measurements available today. This evaluation shows that the predictions output by my model lead to good application performance in practice.

- ~~Fifth~~ ~~Finally~~, As part of my thesis I have produced an 802.11n research platform based on open-source Linux kernel drivers, open-source application code, and commodity Intel 802.11n devices using closed-source firmware that I customized. I have released this tool publicly, and at the time of writing it is in use at 23 universities, research labs, and corporations.

The evaluation is not a contribution, it's a requirement. (:

1.4 Organization of this Thesis

This thesis is organized as follows. In Chapter 2, I provide background information on wireless signals and systems in general, and the IEEE 802.11 standards in particular. Chapter 3 introduces the problem with using channel measurements to predict wireless link performance in today's hardware and using today's techniques, and introduces my Effective SNR-based approach to solving it. In Chapter 4, I develop my Effective SNR model for 802.11n link performance, and demonstrate its ability to handle a wide range of transmitter and receiver configurations as well as wireless applications. I ~~then~~ describe my measurement tool and experimental apparatus in Chapter 5, ~~and~~ ~~then~~ use this platform to evaluate the ability of my model to predict error performance over a single link in Chapter 6. Next, I conduct a detailed study of the model in the context of rate selection for 802.11n in Chapter 7, and then present brief results for a variety of other applications in Chapter 8. I place this thesis in the context of related work in Chapter 9. Finally, I present a brief discussion of the next steps for this work along with concluding thoughts in Chapter 10.

Chapter 2

BACKGROUND

In this chapter, I establish the fundamentals of wireless communication and the IEEE 802.11 standards to the extent needed to understand my thesis.

2.1 *Digital Communication Principles*

Electromagnetic (EM) communications, which send data using *electromagnetic signals*, form the basis of the technologies I will discuss in this thesis. One key aspect of ~~each technology~~ EM comms is which part of the electromagnetic spectrum it uses, characterized by its *carrier frequency or center frequency*, denoted f. ~~Of course, a~~ A fundamental property of radio waves is that the frequency of a wave determines *wavelength* λ according to the relationship $c = f\lambda$, where c is the speed of light. IEEE 802.11 networks typically use EM signals with a carrier frequency in the range of 2.4 GHz and 5 GHz and corresponding wavelengths of about 12 cm and 6 cm.

Data transmission using EM signals works by *modulating* a pure sine wave with frequency f, i.e. by transforming the sine wave to reflect the underlying data. The simplest modulation scheme might be to turn the sine wave on or off depending on whether the bit to be transmitted is a 1 or a 0. The rate at which the signal changes—in this example, the rate the sine wave is turned on or off—is called the *baud rate or symbol rate*, and determines the *bandwidth* of the channel B measured in Hertz (Hz).

In a *link*, that is a sender communicating data to a receiver, the sender generates a signal with *transmit (signal) power* level T that propagates through the *channel* connecting the two. The channel could be a *wire* or it could be the free-space *radio frequency (RF)* environment in which signals propagate from the transmitter's antenna to the receiver's antenna over the air.

2.1.1 *The wired channel*

To simplify the discussion, I will start with the case of a wired channel. The transmitted signal propagates down the wire to the receiver and then is received with *receive (signal) power* S, which I will also refer to as its *amplitude*. While propagating through the wire, the signal gets slightly weaker as a small amount of energy is absorbed. This effect is called *attenuation*, denoted α, and is defined mathematically as the multiplicative decrease in power induced by the channel:

$$\alpha = \frac{T}{S}. \tag{2.1}$$

~~Seems~~ needs a more careful treatment of sources of noise

In addition to attenuation, the wired channel also induces a *phase shift* as the electromagnetic signal propagates. The value of this phase shift, denoted θ, depends on factors including the length of the wire and the frequency of the signal, and is generally considered to be an unknown, uniformly random quantity between 0 and 2π.

Using T for two different properties is a problem.

The signal measured by the receiver is also corrupted by broad-spectrum electromagnetic noise. This corruption is sometimes called *Johnson-Nyquist noise* after its identification in 1927 by Johnson [51] and explanation in 1928 by Nyquist [82], but ~~is~~ it is more commonly known as *thermal noise*. Thermal noise ~~is~~ can be modeled as a complex Gaussian with average *noise power* N (in Watts) equal to

$$N = kTB, \tag{2.2}$$

where $k \approx 1.38 \times 10^{-23}$ (in Joules/kelvin) is Boltzmann's constant, T is the temperature (in kelvins), and B is the bandwidth as described above. This model is also called additive, white Gaussian noise (AWGN).

is AWGN specific to thermal noise?

In the context of 802.11, we typically measure power-related quantities on a logarithmic scale to capture the wide range of possible values. Power levels such as the quantities T, S, and N are usually measured in decibels relative to 1 milliwatt, or dBm, and typically take on values like $T = 20$ dBm and $S = -80$ dBm. To calculate N, we can use Equation 2.2: Wi-Fi links typically use bandwidths B of 20 MHz or 40 MHz, which correspond to thermal noise levels of -101 dBm and -98 dBm at room temperature. In practice, we also assume a 10 dB–15 dB *noise figure*, a quantity that estimates additional noise added by imperfect analog hardware used in receiver processing.

temp?

or x y times 1 milliwatt.

In other words AWGN is unimportant? why describe it then?

AND send hardware as well?

Now that we have defined the signal and noise ~~powers~~ properties of the channel, we can discuss the limits of the communication channel. ~~The seminal works of~~ Ralph Hartley [39] and Claude Shannon [103, 104] proved that the *capacity* of a channel—i.e., the maximum data rate R at which the transmitter and receiver can communicate—is determined by the channel's bandwidth (B as above) and its *signal-to-noise ratio (SNR)*. The SNR, denoted by ρ, is a unitless quantity typically measured in decibels and calculated as

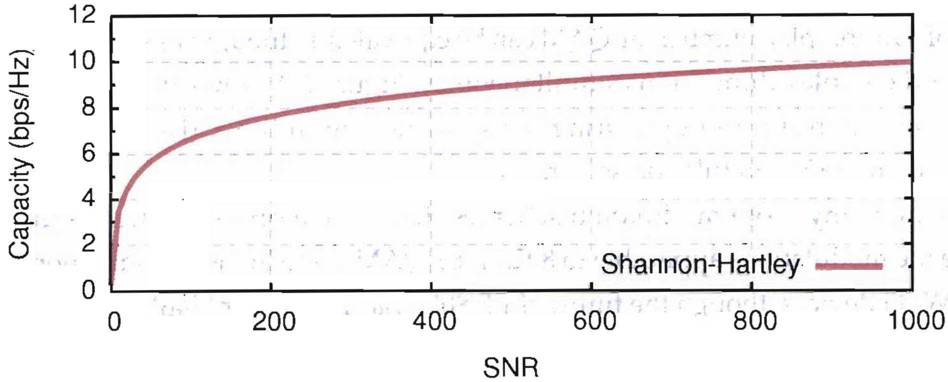
$$\rho = \frac{S}{N}. \qquad \text{eg, } \frac{-80}{10} \tag{2.3}$$

The Shannon-Hartley Theorem [104] establishes what is called the *Shannon capacity* to be

$$R = B \log(1 + \rho). \tag{2.4}$$

Figure 2.1 shows this relationship for the normalized quantity R/B.

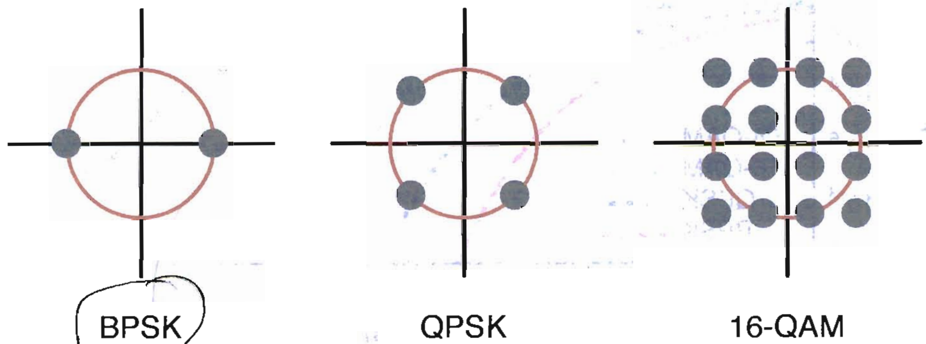
The Shannon-Hartley Theorem determines a bound on the maximum rate achievable as a function of the bandwidth and signal strength. However, it does not give a practical



why not log scale?

Figure 2.1: The Shannon Capacity of a communications channel with Gaussian noise.

but if the noise figure matters?



Put Fig 2.2 on next page

Figure 2.2: Constellation diagrams for the BPSK, QPSK, and 16-QAM modulations. These constellations are normalized such that each modulation has equal average transmit power, indicated by the red circle.

scheme that realizes this bound, and instead systems like 802.11 use ~~a set of~~ many different ~~schemes~~ encodings that achieve different points along the ~~curve~~ y-axis, and choose among these in practice depending on the underlying channel conditions. (OR UNDER)

Need to say - Don't always know N so pick an encoding & comm will work if its under the red line

SETUP YOUR THESIS, ok?

The binary modulation system I discussed above is a scheme called On-Off Keying (OOK). Each symbol conveys 1 bit, and since the symbol rate is directly tied to the bandwidth used by a scheme, OOK can deliver at most 1 bps/Hz. A generalized form of OOK is Amplitude Shift Keying (ASK), which can send more bits per symbol using multiple power levels. m-ASK, i.e., ASK with m power levels per symbol, can deliver up to $\log_2(m)$ bits per symbol and thus can achieve a higher capacity.

As mentioned above, electromagnetic signals actually have both an amplitude and a phase. Amplitude modulation varies one of these parameters, and a complementary scheme called Phase-Shift Keying (PSK) keeps the amplitude constant but varies the phase. A third scheme known as Quadrature Amplitude Modulation (QAM) varies both parameters simultaneously and results in a more efficient system when sending more than 2 bits per symbol. Noting that the polar coordinates given by amplitude and phase can equivalently be thought of as a complex number, m-QAM can be equivalently thought of as $\sqrt{m}$-ASK in both the real and complex dimensions simultaneously. Figure 2.2 shows the two-dimensional *constellations* that result from picturing the symbols sent in BPSK (i.e. 2-PSK), QPSK (i.e. 4-PSK), and 16-QAM modulation schemes.

There are many more modulation schemes than I have presented here, but PSK and QAM are the modulations applicable to 802.11. 64-QAM is the highest modulation currently used by Wi-Fi devices, though the future IEEE 802.11ac amendment [46] will add 256-QAM to this set.

Need a bit more intuition - say: at low SNR, can't distinguish between symbols. At high SNR, ~~can~~ distinguish between many symbols

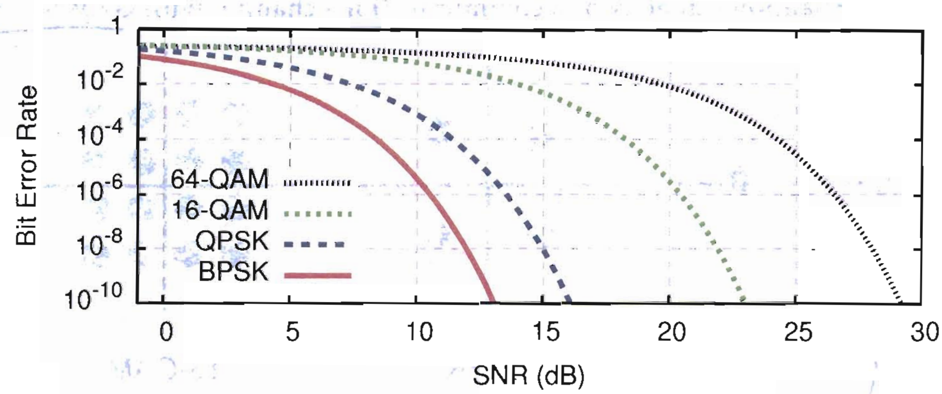


Figure 2.3: The relationship between bit error rate and SNR for the four 802.11 modulation schemes.

I have not yet mentioned the disadvantage of using higher modulation schemes like 64-QAM. When a transmitter uses a modulation scheme that carries more bits per symbol, each bit receives a smaller faction of the total transmitted power and hence is more susceptible to noise. This effect is visible intuitively in the constellation diagrams of Figure 2.2. If the noise is thought of as shifting the received signal along a random vector in the complex space, then ~~it~~ a shorter vector (lower noise power) is required to cause an error by shifting the received signal from near the correct symbol to close to a different constellation point. Figure 2.3 illustrates the magnitude of this effect for the modulations used by 802.11 using textbook formulas [107] that relate the SNR to a bit error rate.

why? Does noise shift the phase? how is that possible physically?

Finally, we can now connect these different modulations back to the Shannon-Hartley Capacity Theorem by examining the capacity achieved by each scheme as a function of SNR (Figure 2.4). In this graph, I assume an idealized coding scheme that delivers the maximum data rate for a given bit error rate; the practical schemes in widespread use today are somewhat less efficient.[1] because ?

[1]Though beyond the scope of this thesis, a number of recent proposals for practical *rateless codes* [33, 86] nearly achieve the Shannon Capacity bound by using much denser constellations and clever coding schemes.

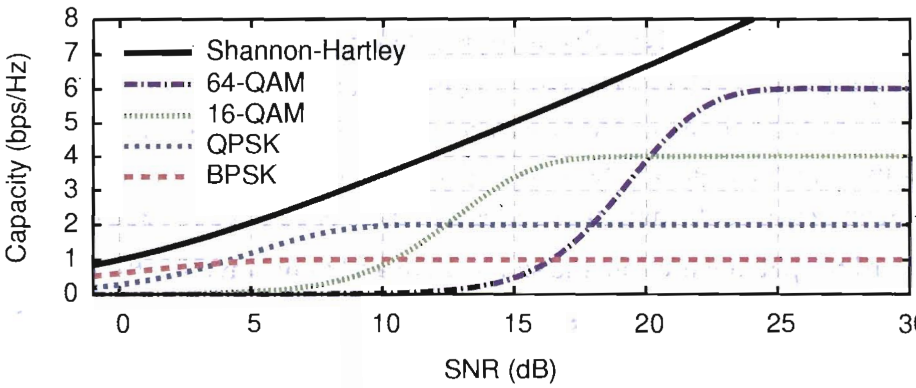


Figure 2.4: The relationship between SNR and capacity for standard modulation schemes and idealized codes.

explain more - at low SNR - high bit loss rate at high SNR, max at capacity of encoding always less than or equal to S-H.

2.1.2 *The wireless channel*

The previous section explained the basics of digital communications in the context of a wired link. Here, I expand to the significantly more complex case of a wireless channel.

In a wireless link, the electromagnetic signal is emitted from an antenna as a *radio wave* that then radiates through the *wireless medium*, i.e. the environment. The dominant source of attenuation in an wireless link is not absorption by the medium, but instead is the three-dimensional spread of energy throughout the environment, of which a small fraction is captured by a receiver's antenna. This effect, called *path loss*, and is captured by the Friis transmission equation, which yields the inverse relationship

$$S \propto \frac{T}{d^n}, \tag{2.5}$$

For omni antennas!

where d is the distance between transmitter and receiver, and n is the path loss exponent. In a vacuum, n would take on a value of 2, reflecting the fact that the energy transmitted at a particular time is spread out over the surface of a sphere (or a different geometric shape in the case of a directional antenna). The path loss exponent varies in different indoor environments, but empirically tends to take on a value between 2 and 4 [107].

This deserves its own sentence - is and directional antennas covered by 2.5? 2.5? w/ n=2-4? why?

Beyond path loss, the most important channel effect is the inherent *multi-path* nature of indoor wireless environments. At 2.4 GHz and 5 GHz, RF signals bounce off metal and glass surfaces that are common indoors. This scattering leads to a situation in which many copies of the signal arrive at the receiver having traveled along many different paths. ~~Because~~ the effect of ~~this~~ RF superpositions depend on the phases of the individual signals. ~~when~~ these copies combine they may add constructively, giving a good overall signal, or destructively, mostly canceling the overall signal.

Again, much less true for directional antennas.

The phase-dependent nature of multi-path effects means that they vary over both frequency and space. For a given distance traveled d, the phase change is $2\pi d/\lambda$. Thus wideband channels may exhibit dramatically different received power levels for different frequencies; such channels are called *frequency selective*. Measurement studies of frequency-selective fading report signal variations as high as 15–20 dB [54]; in Chapter 3 I will present experimental evidence confirming these effects in the environments I studied.

With regard to spatial variation, the small 12 cm and 6 cm wavelengths of Wi-Fi signals means that small changes in path lengths can alter a situation from good to bad. Statistical models tell us that multi-path fading effects are independent for locations separated by as little as half a wavelength. This means that multi-path causes rapid signal changes or fast fading as the receiver moves, or in the case of a stationary node as the surrounding environment changes. Movement at fast speed also induces *Doppler effect*, which aggravates multi-path effects and makes the channel even more variable.

The net effect of multi-path fading is that the received wireless signal can vary significantly over time, frequency and space. This is a problem for good performance because at any given time there is a significant probability of a deep fade that will reduce the SNR of the channel below the level needed for a given communication scheme.

However, an alternative way of looking at the effects of multi-path fading is that they provide *diversity*. In a sufficiently rich multi-path environment, there are so many combining copies of signals that the channel observed on different, nearby frequencies can be considered to be independently faded. For this reason among others, many systems including 802.11 use a scheme called Orthogonal Frequency Division Multiplexing (OFDM). In OFDM, a wide frequency band is split into many *subcarriers* that each carry different modulated bits in parallel, with a higher level error-correcting code across them to take advantage of this *frequency diversity*. By turning a single fast channel into many parallel slower channels, OFDM also sends each symbol for a longer period of time, allowing more time for the channel to average out temporal fades and providing *time diversity*.

Did you explain this? I missed it

Similarly, since antennas separated by at least half a wavelength see independently-faded channels, some Devices? ~~schemes~~ can use multiple antennas to take advantage of the *spatial diversity* these antennas provide. A multi-antenna receiver can realize these gains using clever signal processing algorithms, while a multi-antenna transmitter can use *space-time codes* to provide ~~realize~~ diversity, or—with knowledge of the fading properties of the individual paths between pairs of antennas—can steer its signal such that the multiple copies arriving at the receiver's antenna combine optimally. This process, in which the gain and phase of the signal emitted by each antenna are adjusted (with OFDM, this adjustment may be different for each subcarrier) is called *beamforming*.

Quite confusing

This is too fast unless it doesn't matter?

Finally, suppose that both the transmitter and receiver have multiple antennas. The

Strunk & white – comma if ~~they~~ a, and b where a & b are sentences
no comma (usually) if b is not a sentence.

Italicizing words does not mean you can leave them undefined.

exposition Not clear

foundational work by Foschini, Gans [29] and Telatar [110] in the mid 1990s, introduced *spatial multiplexing*, in which different spatial streams of data can be sent in parallel on different spatial paths. Spatial multiplexing takes advantage of a new, spatial degree of freedom: if each side of a link has at least N antennas, spatial multiplexing can ideally provide an N-fold gain in performance, and results in a modified capacity theorem:

$$R = BN \log(1 + \rho). \tag{2.6}$$

Together, spatial diversity and spatial multiplexing techniques form a set of what are called MIMO (multiple-input, multiple-output) techniques.

There are many other important wireless channel effects. One such is *shadowing*, in which materials such as glass or metal prevent radio waves from passing through. Shadowing is often used to explain how the path loss exponent (Equation 2.5) can empirically be larger than 2.

Another important effect is *inter-symbol interference*, in which some spatial paths are so long that the delayed copies of the signal substantially overlap with the next symbol and make it harder to receive. The delay ~~of the latest~~ between the earliest & latest copy is called the *delay spread* of the channel, and it can be substantial. To compensate for this effect, OFDM systems often repeat each symbol for a period of time called a *guard interval*. If the guard interval is at least as long as the delay spread, the receiver can ignore the inter-symbol interference and still receive a complete symbol.

OFDM systems are more resistant to this effect because the each symbol is transmitted for a longer period, no?

The last important effect to mention is when multiple devices send at the same time in the same frequency band; this *interference* causes a *collision* during which a receiver will measure the sum of both transmissions. There are a number of practical problems for operation during a collision, such as whether the receiver can properly lock onto the desired signal and estimate the effects of the channel on it. In general, however, we can ~~assume these problems are solved and can~~ model the reception probability by replacing the SNR with the *signal-to-interference-and-noise ratio (SINR)*, which treats the interfering signal of power I as another source of noise:

$$\rho_I = \frac{S}{I + N}. \tag{2.7}$$

2.1.3 Summary

In this section, I have presented the fundamental principles of digital communication of wired and wireless channels, including the limits of noisy RF channels and how data is encoded. I have also described the most relevant channel effects that communicating devices must overcome, and the primary techniques used to do so. In the next section, I make this undefined acronym

Maximum

MCS	Modulation	Coding Rate	Data Rate (Mbps)
0	BPSK	1/2	6.5
1	QPSK	1/2	13.0
2	QPSK	3/4	19.5
3	16-QAM	1/2	26.0
4	16-QAM	3/4	39.0
5	64-QAM	2/3	52.0
6	64-QAM	3/4	58.5
7	64-QAM	5/6	65.0

Table 2.1: The single-stream 802.11n modulation and coding schemes. The first seven rates correspond to 802.11a/g rates (excluding 9 Mbps) with four added OFDM subcarriers; the highest data rate uses a new 5/6-rate code. The data rates are given for 20 MHz channels with 4 ms symbols.

huh?

discussion concrete in the context of Wi-Fi by describing the specifics of the IEEE 802.11n standard.

2.2 The IEEE 802.11n standard

The IEEE 802.11 standard is targeted towards defining a mode of operation for a *wireless local area network (WLAN)*, intended to provide medium-range connectivity (≈100 m) using low transmit power (at most 1 W).

These devices use unlicensed spectrum in the 2.4 GHz and 5 GHz bands, and must coexist with consumer electronics such as microwaves, cordless phones, and baby monitors. In addition to this cross-device interference, nearby Wi-Fi networks in separate administrative domains—such as neighboring apartments—may ~~need to share~~ transmit on the same channel. As a result, Wi-Fi networks are not planned in a centralized fashion, but rather use decentralized protocols that work towards a good solution in a distributed fashion. For instance, 802.11 includes a *carrier-sense multiple access (CSMA)* protocol to manage which devices send: in essence, a transmitter listens to ensure no other devices are transmitting before sending a packet, and reduces its sending probability exponentially (via *exponential backoff*) if its transmission is not acknowledged.

At the physical layer, 802.11 uses the modulation schemes and OFDM as I described above, operating over 20 MHz channels. In conjunction with different modulations, 802.11n also uses error-correcting codes with different *coding rates* to achieve different operating points in the rate-robustness tradeoff space. I summarize the specific single-stream configurations in 802.11n as well as the resulting link data rates in Table 2.1.

you described many schemes & 802.11 consists of many standards

don't you think that's worth mentioning?

at least justify why 802.11n → the intro made the point 802.11n differs significantly from the others for the purpose of the thesis.

The 2009 standard amendment to IEEE 802.11n [44] added functionality and protocols for multi-antenna techniques such as spatial diversity, spatial multiplexing, and beamforming undefined

Enhancement	Gain	Description
Short OFDM Guard Interval	1.11×	Data can be more efficiently encoded when the multi-path delay spread is low.
Spatial Multiplexing	2× to 4×	Up to 4 concurrent spatial streams.
Wider 40 MHz Channels	2.08×	More bandwidth, higher capacity (Equation 2.4).
Beamforming	??	A sender with multiple transmit antennas can shape its signal to match the RF channel, improving both performance and reliability.

right justify table elements if they are l-vec

Table 2.2: IEEE 802.11n adds a number of enhancements to the base single-stream configurations depicted in Table 2.1.

~~as I described them above~~. The ~~802.11n~~ se enhancements are shown in Table 2.2. Most of improvement in the maximum data rate—from 54 Mbps in 802.11ag to 600 Mbps in 802.11n—comes from the ability to use wider channels and multiple spatial streams. Together, these add $2 \cdot 2 \cdot 4 = 16$ times as many configurations to the space of a single link. Beamforming is effectively an analog parameter and adds nearly unbounded options.[2]

why 16? why would anyone use a narrow channel?

Table 2.2 shows ~x factor of c => how do get 12x?

The hardware/software interface in 802.11n operates at the level of individual packets or continuously-transmitted batches of packets.[3] Packets are sent to the hardware and transmitted over the air. The receiver detects a new transmission from the increase in energy, estimates the parameters of the wireless channel from the packet's standard, known preamble, and then decodes the packet. The standard behavior for 802.11 links is that all bits—after error-correcting ~~decoding~~—must be correct in order for a packet to be received, otherwise the packet is dropped by the hardware. Correctly received packets are delivered to the software layer in conjunction with physical layer configuration information about the transmission (e.g., what MCS in Table 2.1 was used) and reception (e.g., which receive antennas were used) of the packet, plus physical layer metrics of link quality.

The standard link metric is the *receive signal strength indicator (RSSI)*. The RSSI was included in the 802.11 standard from the beginning as "a measure by the [physical layer hardware] of the energy observed at the antenna used to receive the current [packet]" [43, §17.2.3.2]. There are no specified requirements on its accuracy, instead, it is only required to be "a monotonically increasing function of the received power" [43, §17.2.3.2], and is generally used by the hardware to tell whether another device is transmitting.

[2]For transmitter and receiver each using 4 antennas on a 40 MHz channel, representing the beamforming matrices at maximal resolution takes 29,184 bits.

[3]I mostly ignore batching in this thesis.

Isn't the resolution a function of the hardware? and the # of OFDM channels?, not the overall channel size?

2.3 Summary

In this chapter, I have presented the background information to provide a basic understanding of wireless channels and the specific IEEE 802.11n technology used to operate in them. As I ~~made clear~~ described in Section 2.1.3, there are many different techniques that a transmitter and/or receiver can use to achieve robust operation in indoor wireless channels. However, the challenge—and the focus of most Wi-Fi research—is to decide which techniques to use, when to use them, and how to configure them to obtain the best operating point given the actual properties of the wireless channel ~~the link is currently operating in~~. This is the primary problem I tackle in this thesis; in the next chapter I describe this problem in detail and given an overview of my approach.

let the reader judge clarity

Towards end of chapter, from end of p. 18 onward you start racing. Slow down! There isn't a page limit.

Um, you also tackle config for multiple links, no?

This distinction isn't important — neither works! Not that it is too specific or too general. But that one requires testing all combos. AND the other has to work (and doesn't today)

Chapter 3

PROBLEM AND APPROACH

The problem I study in this thesis is how to inform configuration decisions for wireless networks. I begin this chapter by presenting some of the primary problems in this space.

Next, I discuss how we handle these challenges today. There are two primary classes of techniques: (1) *statistics-based* schemes which only use packet reception or loss as a ~~high-level~~ indicator of the ~~correct~~ suitability of an encoding for a specific channel ~~channel performance~~, and (2) *channel-based* schemes which use measurements of the RF channel to predict packet delivery. Generally, ~~the former statistics-~~ packet ~~loss~~ delivery or loss is ~~are~~ too specific, because ~~a packet probe~~ success in one configuration says little about whether another configuration—say, at a different rate or antenna mode—will also work ~~similarly~~. ~~The latter~~ RF channel measurements ~~are too general~~ provide, ~~because~~ the ~~data recorded~~ techniques used today ~~and the way they are~~ are too applied ~~only~~ coarsely to work well. ~~reflect the true behavior of wireless operation over the underlying RF channel~~. offer the potential for predicting the performance of a config w/o testing it, but

are these your names? they seem unsuitable => both use info about the channel & both use statistics!

I conclude this chapter by presenting ~~the hypothesis of my research and my approach~~ to ~~demonstrating~~ it. My hypothesis is that it is possible to unify wireless configuration decisions into a single framework that is simple and incurs little overhead, but is still accurate. To do so, I develop a comprehensive system that uses low-level RF channel measurements in conjunction with a simple but powerful model ~~that can~~ to predict the performance of $\boxed{\text{every}}$ operating point in the entire configuration space.

Every is a big word. Really? Isn't it specific to 802.11n but approach is general

3.1 Problem: Rate Control for a Single Link

To accurately choose the rate at which to send data wirelessly, a rate control algorithm must find a good option among many possibilities. With 802.11n, ~~which has adopted~~ and its modern multi-antenna and physical layer techniques, this problem has gotten significantly more complex. To illustrate this, Figure 3.1 shows the available rate configurations in 802.11n for a device with three antennas. These configurations use the eight modulation and coding scheme (MCS) combinations described in Table 2.1 and the 802.11n enhancements shown in Table 2.2.

At the bottom of the figure, the SIMO line shows the eight single-stream configurations, which provide rates ranging from 6.5 Mbps to 65 Mbps. These are precisely the eight choices for rate that algorithms controlling a legacy 802.11a/g system can ~~must~~ choose from.

~~In contrast~~, this space expands by a factor of 12 with 802.11n. Adding a second (MIMO2) and third (MIMO3) spatial stream increases the maximum rate to 195 Mbps, for a total of

with three antennas? (we ignore ~~spatial~~ beamforming for now)

Also say — no monotonic b/c this: p-path through different configs ~~& at~~ may yield better ~~pack~~ packet loss, or worse even at the same rate

OTOH — skeptical reader will say — n. b33ie, always use HT40 + MIMO3? → why not? So then SGI is upper & it's just 16 configs! ~~Note that~~ ~~it~~ 8 must & those can be quickly nulled out (es if SGI doesn't help) Problem solved?

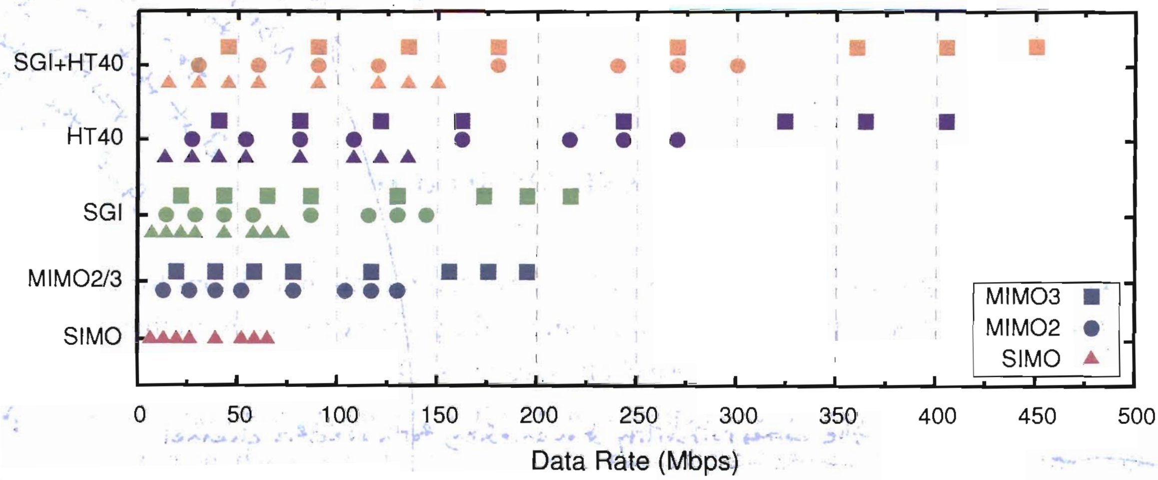
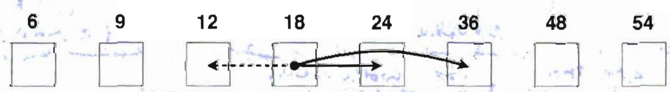


Figure 3.1: The different rate-related 802.11n configurations that use three antennas and 802.11n physical layer enhancements.



next page

Figure 3.2: A typical rate adaptation search pattern for 802.11a.

24 different configurations. For each of these configurations, 802.11n adds the optional use of double-width (40 MHz, HT40) channels that raises the maximum rate to 405 Mbps with 48 choices. Finally, a physical layer tweak to a shorter OFDM guard interval (SGI) adds another ≈ 11% and pushes the fastest configuration to 450 Mbps among 96 possibilities.

Looking forward, ~~though three antennas are common today 802.11n can support up to four.~~ the standard w/ four antennas, The next amendment to 802.11 (802.11ac) will add two new single-stream rates ~~using the~~ 256-QAM modulation, plus channels of up to 160 MHz bandwidth. Combined, 802.11ac will comprise 320 configurations—a factor of 40 more than 802.11a. And beamforming. For the foreseeable future, the dramatic expansion in the rate space will continue as wireless technology ~~improves.~~ evolves.

Now having defined the basic problem of rate control, in the next two sections I describe the statistics-based and the channel-based approaches to solving it.

3.2 Existing ~~Statistics~~ Packet Loss-based Approaches

The majority of rate control algorithms today rely on packet loss statistics to adapt the operating rate. These algorithms use ~~a large~~ the number of losses as a signal ~~that~~ of the link quality. With too many losses, the channel is too poor to support the current rate, and ~~hence~~ the system should fall back to a lower rate ~~that is more easily received~~. Conversely, when a link experiences a very small number of losses using its current rate, it sends some *packet probes* at a new faster rate, and switches to the faster rate if ~~it also works well~~ those probes succeed. Figure 3.2 shows a typical 802.11a adaptation search pattern, where each box corresponds to an 802.11a rate and the arrows show the faster (solid) and slower (dashed) rates that might be probed.

The first algorithms (ARF [56] and AARF [65]) would only switch between a rate and the next fastest or slowest; later implementations look up to two rates ahead [15]. Minstrel [108], the dominant 802.11a rate adaptation algorithm used today, performs intelligent (biased) sampling of *all* rates to keep up-to-date estimates of the global rate space and can thus take discontinuous jumps. Recent revisions to these algorithms have focused on better handling of corner cases, such as improving performance ~~during~~ when there is interference due to hidden terminals via adaptive control over RTS/CTS [108, 122].

confusing

Some algorithms ~~use~~ have been proposed to use bit error rate statistics instead of loss rate statistics to adapt rate. SoftRate [119] estimates the bit error rate using a soft-output Viterbi decoder for error correction, and Chen et al. [22] designed a coding scheme called Error Estimating Coding (EEC) to enable accurate BER estimation at a higher layer.

3.2.1 *Complication: Multi-dimensional Search Space*

All of the statistics-based approaches, which walk up or down the list of rates based on whether the current rate works well, implicitly rely on the following basic assumption (outlined by Vutukuru et al. [119]):

You need to make a stronger argument that there is likely to be no simple decision procedure based on packet loss.

Assumption: *BER is a monotonically increasing function of the bit rate.*

But 802.11n rate configurations are *non-monotonic*. That is, it is not necessarily true that faster configurations are generally less likely to work than slower ones. This violates the axiom of these statistics-based approaches, and hence the *multi-dimensional* search space must be treated as such. I explain why in the following example.

The way you've said it, it's obviously not true — but plots show algorithms could still work. Eg, 40MHz is not more likely to have errors than 20MHz so isn't that true, or nearly so?

Figure 3.3 shows three plausible *rate maps* for 3-antenna 802.11n links. In these rate maps, each row represents a different number of spatial streams, and each column represents a different MCS. A cell is shaded if a link can reliably deliver packets using that rate at that number of streams. The black box corresponds to MCS 12—2 streams at 39 Mbps each—which is the highest working 2-stream rate for these three hypothetical links.

In 802.11n, each of the scenarios (A), (B), and (C) illustrated here is possible. In particular, if the link can reliably deliver packets using MCS 12 then it is likely that MCS 4—the same encoding, but fewer streams—works as well. The same holds for MCS 11, since it uses the same number of streams but a less dense encoding. Similar logic implies all the shaded cells in link (A), which represents the most conservative situation in which MCS 12 works well. Conversely, link (B) exhibits the best corresponding situation; higher-encoding single-stream configurations may also deliver most packets, and there may be little penalty from using 3 streams, thus resulting in the same set of 3-stream links working. Finally, link (C)

How can 3 streams fail if 2 streams works? you haven't explained that.

You should also argue that probing takes time & bw ⇒ takes several probes to see if you are at the right rate, since a single success or loss isn't determinative.

rate not total bw

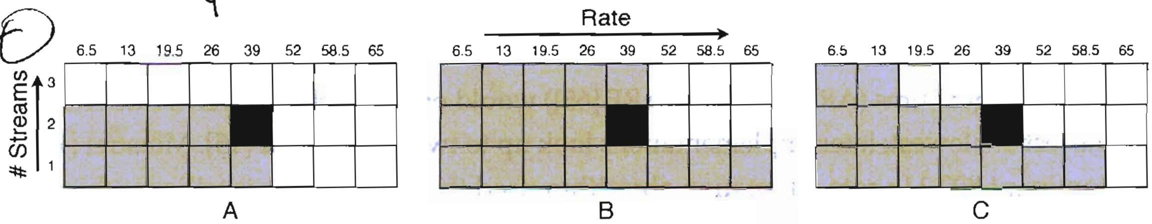
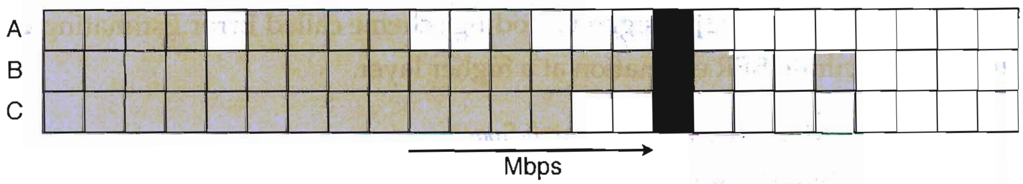


Figure 3.3: Three different rate maps for 802.11n links. On these links, MCS 12 (the black box) is the highest reliable 2-stream rate, and gray boxes indicate other reliable transmit configurations. A (*left*): the worst possible situation in which no 3-stream rates and no higher single-stream configurations work. B (*middle*): the best case in which all single stream rates work and all 3-stream rates work up to 39 Mbps each. C (*right*): an average case in which the set of reliable rates decreases as more spatial streams are used.



But this would be a stupid way to go about it? why compare yourself to a stupid algorithm? it's clear from 3.3 that there are constraints.

Figure 3.4: Rate maps for the links in Figure 3.3 now mapped into one dimension and sorted by total link speed (Mbps). In this view, the strict monotonicity assumed by rate adaptation algorithms is violated, and the violations occur in a channel-dependent way. Thus, 802.11n rate adaptation requires optimization along multiple dimensions.

ok this is total bw NOT rate

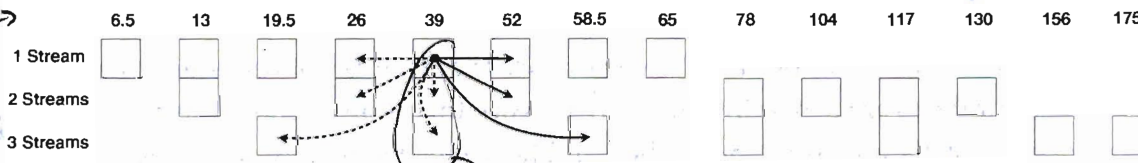


Figure 3.5: A typical rate adaptation search pattern for 802.11n. what is dash vs. solid?

why increase streams is same as decreasing rate w/ one stream? seems backward.

don't you think that's worth explaining?

exhibits an average case, in which lower rates must be used as the number of spatial streams increases.

The key is that each of these three links is plausible, which means that the search space for rate is non-monotonic in 802.11n. In Figure 3.4, I have redrawn the rate maps for these three links along a single-dimension, sorted by data rate. Ties in pure data rate—e.g., MCS 1 vs MCS 8, both at 13 Mbps—are broken such that fewer streams is lower in the search. Here we can see that for all three links there exist higher rates that work well where lower rates do not. Thus a rate configuration algorithm for a multi-antenna link needs to consider a multi-dimensional search space. ?

3.2.2 Current 802.11n Statistics-based Approaches

Figure 3.5 illustrates the multi-dimensional search challenge with a concrete example. Each row corresponds to a transmit configuration with one, two, or three spatial streams. The

In other words, you don't have as many choices from each state as before (as implied by 3.1) its 3-5x.

So the reason for your work isn't the inefficiency of rate adaptation – its that effSNR allows you to do more efficient rate adaptation? or perhaps you don't need it at all?

eight boxes correspond to the eight 802.11n MCS combinations, placed in columns that reflect the aggregate link speed.

As we saw in Figure 3.2, the single-dimensional search algorithm might try one or two rates higher, and during periods of loss it might fall back to the next lowest rate. In contrast, when increasing 802.11n rate from a single stream at MCS 4 (39 Mbps), the configurations MCS 5 (52 Mbps), MCS 11 (MIMO2-52 Mbps), and MCS 18 (MIMO3-58.5 Mbps) are all transmit configurations with better link speed, and each might work or not work depending on the channel. When MCS 4 experiences loss, there are five choices of fallback configuration. This includes the higher-stream MCS 10 (MIMO2-39 Mbps) and MCS 17 (MIMO3-39 Mbps) which both have the same link speed and might work, as they use more robust modulation and coding combinations.

if they would usually work better at the same rate, why would you be in MCS 4?

MiRA [83] is a recent research algorithm that implements a version of this multi-probing scheme, as does the Minstrel_HT [28] algorithm used by the Linux kernel to do 802.11n rate selection in practice. A third approach is used by Intel's iwlwifi driver [48], which uses an 802.11a-like algorithm to select between MCS using a fixed number of streams, and adjusts the number of streams at coarse intervals.

Other ~~Rate loss~~ Bit Error

3.2.3 ~~State of the Art in~~ Statistics-based Approaches

Not really state-of-the-art if they don't handle 802.11n no?

The dominant algorithms used in the Linux kernel today are Minstrel [108] (for 802.11a/g) and Minstrel_HT [28] (for 802.11n). In general, statistics-based schemes provide good performance for static links in which the devices do not move and the surrounding environment does not change. For such cases, the algorithms may be inefficient at first but will converge to a good operating point. The challenge, as pointed out by several works [42, 54, 119], is that—depending on the speed at which devices move or the environment changes—these algorithms may be slow to react to varying conditions in mobile links environments, resulting in significant performance degradation, in those cases.

SoftRate [119] and EEC [22] are the newest BER-based adaptation algorithms. Both algorithms provide faster adaptation than their loss-based counterparts because by using the BER they can distinguish between a rate that is barely working with marginal BER (in which case the next fastest rate will not work) ~~or~~ and a rate that has a lot of headroom (in which case it is worth probing the next fastest rate). These algorithms perform well at shifting up and down within a monotonic rate space; however, their BER estimations do not apply across the orthogonal dimensions such as multiple spatial streams. To handle 802.11n, these algorithms would need to be amended to do multi-dimensional search as well.

|| between A or B? you have "between noun or verb

seems obvious that this would help - orthogonal to issue of ~~problem~~ # of configs that need to be probed

The key to 3.2 is the table in 3.3. But it is stated as fact w/o evidence!

You also don't say that systems w/ 802.11 did multi-rate probing in the background - presumably because it was sometimes helpful to do multi-rate jumps. The fan out in 3.5 is more of an issue in that case, but even so, seems like ~~you would~~ best case would be the initial wifi-probe to determine best rate at current # of streams & also figure out how many streams to use. That doesn't seem so bad, does it?

3.3 *Channel-based Approaches*

The second class of approaches to configuring rate use channel information to guide rate selection or adaptation. As I described in Chapter 2 (Figure 2.3), textbook analyses of modulation schemes give delivery probability for a single signal in terms of the signal-to-noise (SNR) ratio [30]. These theoretical models hold for narrowband channels with additive white Gaussian noise. They predict a sharp transition region of 1–2 dB over which a link changes from extremely lossy to highly reliable. This feature in theory makes the SNR a valuable indicator of performance.

you defined AWGN as thermal noise, not gaussian noise in general

This gives rise to a simple SNR-based configuration scheme, at least for selecting rate: Upon receiving a packet, a device can use the measured RSSI to compute the *Packet SNR* and predict the fastest rate supported. It can then feed this information back to the transmitter, which will use the newly selected rate for subsequent transmissions. This approach was explored in simulation by Holland et al. [42] with an algorithm called RBAR, and shown to work well.

3.3.1 *Complication: Packet Delivery versus SNR in Practice*

Though SNR-based rate control algorithms may work well in simulation, subsequent practical work found that the Packet SNR computed from RSSI was unreliable [4, 94, 126]. In very early devices, the RSSI was found to vary wildly over time or device temperature, providing unreliable thresholds; this was corrected by calibration in later devices (e.g., confirmed by Zhang et al. [125] and by my measurements). Reis et al. [94] found that RSSI estimates were corrupted by interfering transmissions. Finally, even in the absence of these latter effects, several studies found that the same RSSI value gives dramatically different performance for different links.

Alternately you could quantify the ~~bit errors~~ bw lost due to probing and/or being at the wrong bw: is it ~1% effect? 10% effect? very hard to tell from the discussion.

To understand which effects still hold for 802.11n hardware, I generated performance curves using an Intel Wireless Wi-Fi Link 5300 a/g/n (I describe my experimental platform in Chapter 5) wireless network card. I connected two network cards together via a wire, and configured them to operate in a mode that uses a single antenna to transmit or receive. Using an inline variable attenuator I varied the amount of power received, and for each power level I sent around 1,000 packets using each of the eight 802.11n single-stream rates (Table 2.1) and measured the fraction of delivered packets, the *packet reception ratio (PRR)*. With these measurements, I plotted the PRR against the link's SNR (computed from RSSI measurements at the receiver), and present the result in Figure 3.6.

This figure shows a characteristic sharp transition region between SNR values at which the link goes from lossy to working, 2 dB at low modulations up to 4 dB for the fastest 65 Mbps rate. There is also a clear separation between rates: at a given SNR value, it is clear which rate should be used. This wired link provides a good approximation of a theoretical

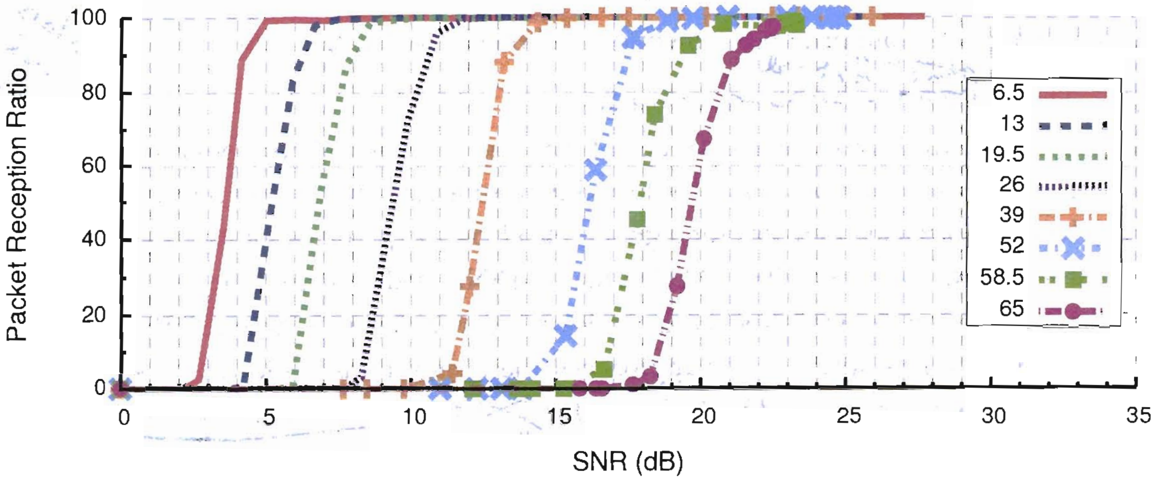


Figure 3.6: A wired 802.11n link with variable attenuation has a predictable relationship between SNR and packet reception rate (PRR) and clear separation between rates.

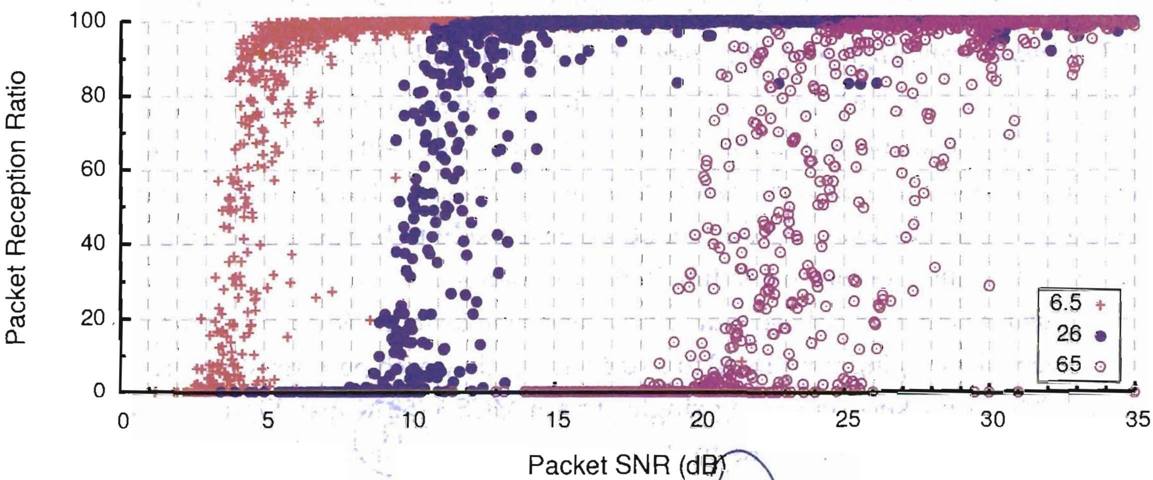


Figure 3.7: Over real wireless channels in our testbeds, the transition region varies by 10 dB or more. The wireless channel loses the clear separation between rates. ~~(and so~~ only three rates are shown for legibility~~)~~.

narrowband channel despite the relatively wide 20 MHz channel, the use of 56 OFDM subcarriers, coding and other bit-level operations. This is the behavior we would want from a link metric in order to predict packet delivery.

In contrast, packet delivery over real wireless channels does not exhibit the same picture. Figure 3.7 shows the measured PRR versus SNR for three sample rates (6.5 Mbps, 26 Mbps, and 65 Mbps) over all wireless links in our testbed~~s~~, using the same 802.11n NICs. The SNR of the transition regions can exceed 10 dB, so that some links easily work for a given SNR and others do not. There is no longer clear separation between rates. This is consistent with

testbeds? or testbed

⇒ um, there is a clear separation, at least if you want a high PPR

it's not the separation that's the issue – its the # of probes needed to determine the correct rate, when even the optimal rate has close ... &

In several ... you ... because it doesn't work in 802.11n. You should generalize
ignore prior results because it doesn't work in 802.11n.
this point in the intro & in Chap 2. its not just the larger # of configs
its also the higher rates & denser encodings that undermine, say, the
results in 3.3.2. You also miss a contribution in Chap 1
→ characterizing channel behavior in 802.11n
(presumably not done before?)

Same point in 3.4 → lots of prior work, not updated in 802.11n. It's unclear if they won't work in 11n or it would be inefficient or what. But main point is to stress challenge is 11n.

the measurements from prior work mentioned above [4, 54, 94, 125, 126].

3.3.2 *~~State of the Art in SNR-based~~ other Hybrid Approaches*

Although prior studies and my measurements showed that Packet SNR does not accurately predict delivery across links, they also found that for a particular link a higher SNR generally has higher packet delivery for a given rate [4, 54, 125]. Consequently, there are two algorithms, SGRA [125] and CHARM [54], that use SNR feedback from the receiver in conjunction with packet loss statistics in order to learn the relationship between SNR and packet delivery online. Like statistics-based approaches, these algorithms work well for static links. Additionally, they provide good performance for fixed devices in mobile environments [54], because the learned relationship between SNR and PER is only slightly affected by moving objects and the learned calibration is generally valid. Successive measurements by Vutukuru et al. [119] showed that CHARM ~~tended~~ tends to under-select in mobile links because it ~~was~~ is unable to adapt its thresholds quickly enough to respond to the changing channel.

oxymoron?

so we're done?

why change tense

3.3.3 *Complication: High-level Measurement of Low-level Subchannel Effects*

I listed above several reasons that Packet SNR calculated from RSSI has historically been a poor predictor of performance. In the modern era of calibrated hardware, however, measurements no longer vary significantly with changing temperature or power level, or across devices. Instead, the dominant factor is likely to be the use of OFDM, and the presence of frequency-selective fading in the RF channel.

Does this issue apply to the results in 3.3.2? If so, say so!

802.11g doesn't use OFDM?

To illustrate this fact, I chose four representative links in my 802.11n testbed. These four links have SNRs ranging from 16 dB to 30 dB and yet they each perform similarly, delivering around 80% of packets sent using single-stream MCS 6 (52 Mbps). Figure 3.8 shows the packet reception rates and SNRs for these four links; but it also includes the SNRs of the individual OFDM subcarriers for each links.

Comma splice

With this detailed picture, we can see that multipath causes some subcarriers to work markedly better than others although all use the same modulation and coding. These channel details, and not simply the overall signal strength as given by SNR, affect packet delivery. The fading profiles vary significantly across the four links. One distribution is quite flat across the subcarriers, while the other three exhibit frequency-selective fading of varying degrees. Two of the links have two deeply-faded subcarriers that are more than 20 dB down from the peak.

Because of these different fading profiles, these links harness the received power with different efficiencies. The more faded links are more likely to have errors that must be repaired with coding, ~~and~~ or require extra transmit power to compensate. Thus, while the performance is roughly the same, the most frequency-selective link needs a much higher overall packet SNR (30.2 dB) than the frequency-flat link (16.5 dB). This difference of almost

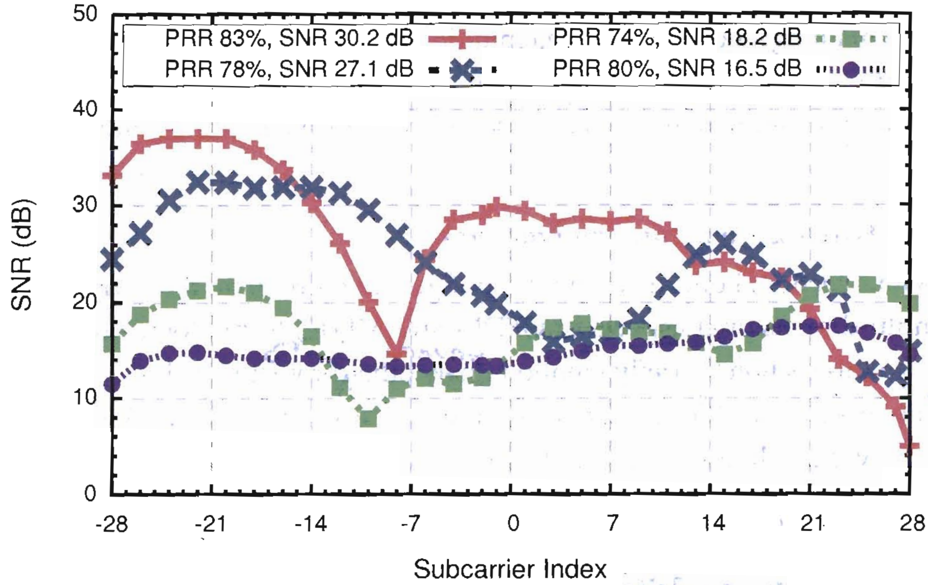


Figure 3.8: Channel gains on four links that perform about equally well at 52 Mbps. The more faded links require larger RSSIs (i.e., more transmit power) to achieve similar PRRs.

Does this mean the results in 3.3.2 are invalid for 802.11n? You haven't explained why channel diversity is a stable property of an environment, so that you can calibrate for it, or the change/tradeoff.

14 dB (more than 20×) highlights why Packet SNR based on RSSI does not reliably predict performance.

To exacerbate this issue, 802.11n adds MIMO techniques to the network. During a multi-stream transmission, the receiver still records only one RSSI value per antenna. This RSSI (and the resulting SNR) reflects the total received power combined across all subcarriers and all spatial streams. The total power received will vary with the number of streams, and the actual performance of the link will depend on how well this total power is balanced across spatial streams and how well the receiver can separate the two spatial streams. Thus in 802.11n Packet SNR is likely to be even less accurate when predicting link performance.

would be nice to have data to show this :)

3.3.4 *Approach using Low-level RF Measurements*

AccuRate [102] takes an alternative approach to using physical layer information to predict performance. Instead of measuring information about the *signal power*, AccuRate measures the *error vectors* (described in Chapter 2) of the received symbols when demodulating a packet. To make predictions about bit error rate, AccuRate then replays those same error vectors to a physical layer simulator, which models the reception of a packet using each of the different rates and selects the fastest successfully received packet. Though it would be impractical to implement a full physical layer simulator for each received packet, AccuRate was shown to be significantly more accurate than SNR-based algorithms with performance comparable to SoftRate. At the same time, AccuRate suffers from the same 802.11n-related

I'd combine this with 3.3.2 → its use of fine-grained information about a probe is the same, you just use less info in the choice/tradeoff.

Isn't channel width always better?
AND can't AccuRate probe each of the different # of antennas & then compute the result.

For the guard interval, that seems directly measurable - either the environment has multipath or it doesn't. It's not likely to swap back & forth quickly.

flaws as the remaining algorithms: the magnitude of the error vectors will change depending on different numbers of spatial streams or channel widths or the use of a short guard interval, and AccuRate can handle none of these cases without implementing a multi-dimensional search.

3.4 *Further Wireless Configuration Problems*

In the previous section, I outlined the rate configuration problem, the current approaches, and the multi-dimensional aspects of OFDM and MIMO technologies that make them ineffective. In this section, I briefly mention ~~many~~ several other config problems and how they are solved ~~in~~ Wi-Fi networks today. (For a deeper discussion of each, see Chapter 9.) Together, these problems show the richness of the wireless network configuration space.

less?

too strong
effective?
efficient?

3.4.1 *Antenna Selection*

A transmitter sending fewer spatial streams than it has transmit antennas may wish to ~~choose~~ use only a subset of ~~those~~ the available antennas to save power or improve performance. Among production 802.11n drivers in Linux, only Intel [48] has such an algorithm; within a fixed number of streams it occasionally probes the different transmit antenna configurations. In this algorithm, switching between transmit antenna sets occurs on timescales of seconds.

How would it improve performance to use fewer antennas?

In the analogous scenario on the receive side, some chips automatically use only a subset of receive antennas when receiving a packet instead of fully maximizing available spatial diversity. These algorithms typically use Packet SNR measurements of the antennas to determine when additional antennas will add little gain. (Of course, this determination can be erroneous in the face of subchannel fading effects.)

3.4.2 *Channel Width Selection*

When both devices in an link support multiple channel widths, they may obtain better performance or power savings depending on the bandwidth they choose. SampleWidth [21] uses a probing algorithm to determine which width gives the best performance, aiming to achieve spectral isolation from interferers. For choosing between 20 MHz and 40 MHz bands, the algorithms in Linux tend to integrate channel width selection into the rate selection algorithm. When both widths are available, Intel's driver, which coarsely switches between different numbers of spatial streams, doubles the set of modes it probes by instantiating one copy for each potential bandwidth.

?!

You never mentioned why channel width will have a non-predictable consequence on performance.

3.4.3 *Transmit Power Control*

Some? ~~D~~evices can adapt their transmit power levels to save energy or reduce interference with other nodes. In practice, however, all drivers seem to aim to optimize performance of their link. ~~To that end,~~ Reducing transmit power can ~~only~~ reduce the maximum rate of the link and make interference worse by creating more hidden terminals; so this is never done in

and reduce transmit power only if it does not affect performance.

never is a strong word

what if I'm an 802.11n talking to an 802.11a?

So its not a config issue! Are you saying it should be?

practice. Research proposals to achieve these ends typically rely on sampling performance and/or interference at various power levels. which ends?

3.4.4 Access Point Selection

When clients select which access point to connect to today, a number of factors are important, including both the quality of the link to the access point and also the load on that access point. Clients today typically choose access points solely based on the measured Packet SNR, on the assumption that it's a good proxy for downlink performance. Some proposed enterprise AP systems (e.g., DenseAP [77]) can take load into account as well.

One interesting note is that today's algorithms are not heterogeneity-aware. Consider ~~So given~~ a choice of two APs: (1) with 30 dB SNR and 3 antennas, ~~which would offer a rate of 250 Mbps~~, and (2) a closer AP with 35 dB SNR but only 2 antennas, ~~and supports only 100 Mbps~~, today's clients will ~~still~~ choose AP (2) with the larger SNR, even though the first may provide better bw depending on subchannel fading effects...

Isn't this also 3.4.2?

3.4.5 Channel Selection

Channel selection is the problem of choosing the best operating frequency for a pair (or set) of wireless devices. This is not a runtime choice in today's access point networks, because the frequency is chosen by the AP. However, channel selection ~~this~~ is likely to be a problem ~~now that~~ in device-to-device ~~connections are desirable in~~ networks e.g., Wi-Fi Direct ~~networks~~. (I note that algorithms have been proposed for the related problem of distributed access point channel assignment to manage load and interference (e.g., [5]).)

set statically when the APs are configured?

? obscure reference - if its worth mentioning, its worth explaining

3.4.6 Multi-Hop Routing

~~Evaluating~~ Increasingly ~~how well~~ Multi-hop paths works? will be needed in device-device networks, ~~through a wireless network is also irrelevant to today~~'s AP ~~networks~~. Most work in this space th~~erefore applies to mesh networks, and usually~~ uses a combination of probing, Packet SNR-based heuristics, and state space reduction (e.g, assuming single-antenna devices and a single fixed rate network-wide). One more practical recent proposal by Bahl et al. [11] uses relays to address the rate anomaly problem in Wi-Fi access point networks, and uses Packet SNR to predict bitrate and calculate how well paths work. The performance of these solutions depends on the accuracy of these heuristics, which have not yet been adapted for heterogeneous devices or been made MIMO-aware.

but are not in today's AP nets.

obscure reference

which? Bahl's? the others?

You make this point in more detail in Chap 1 - why repeat it here in less depth?

3.4.7 Spatial Reuse

Spatial reuse is the problem of managing concurrent transmissions that occupy the same frequency. In today's access point networks, algorithms typically aim to have only one transmission at a time and adaptively turn on RTS/CTS when necessary to eliminate hidden terminals that hurt performance. A state-of-the-art algorithm to promote spatial reuse is CMAP [120], which fixes the entire network to homogeneous single-antenna devices

why not describe it before slamming it?

34) way too obscure - no one will know what you are saying except "Other work bad." - why isn't an adaptive system appropriate? why is CMAP better? is it better?

using the same rate and still ~~required~~ a complex distributed probing algorithm in a static environment to achieve good performance.

why past tense?

3.4.8 Beamforming

have been? will be? can be? shouldn't be?

Finally, there is the problem of beamforming, that is, for a transmitter to shape the combined signal sent out its antennas so that the spatial paths best combine at the receiver. Theoretical gains from beamforming are evaluated by measuring the increase in Shannon capacity using ideal hardware and optimal receiver, rather than by the practical constraints of real hardware. I do not know of any practical systems for Wi-Fi that use this type of beamforming. ~~but~~ Such a system would need a way to ground the output of the theoretical model to evaluate how the link would work in practice. Rather than an abstract complaint, there are real issues such as the tension between the optimal "water-filling" algorithms for beamforming [114] (which allocate power unequally across antennas or subcarriers) and practical hardware constraints such as amplifier peak-to-average-power limits.

So you're going to come up with a practical beamforming design here? If not, seems like a distraction ~~use~~ not worth it or at least, refer to what to expect

In practice, I imagine that this grounding would be done by probing the link performance, as has been the case with analog beamforming strategies [72] that operate in a fundamentally different way than 802.11n-like beamforming.

3.5 My Approach: an Effective SNR-based model for Wi-Fi

My hypothesis is that *it is possible to unify the decision-making components of wireless network configuration algorithms into a single comprehensive framework that is practical and provides good performance.* I ~~envision~~ develop a framework that is flexible enough to handle all the problems discussed in this section. ~~To demonstrate this hypothesis~~, I ~~develop a comprehensive system~~ ~~that~~ The framework uses low-level RF channel measurements in conjunction with a simple but powerful model that can predict the performance of every operating point in the entire configuration space.

In this thesis

including beamforming?

See comments in Chap 1 - this seems too broad since thesis concerns challenges of 802.11n & future nets.

In particular, I develop a practical methodology that uses low-level measurements of the RF channel and the concept of an Effective SNR [78] to predict performance for wireless channels that use modern physical layer technologies such as OFDM, multiple antennas, variable channel widths, and spatial diversity and multiplexing. I also explain how to apply this prediction engine to a wide variety of link and network configuration problems such as those described in this chapter. To demonstrate that this methodology is practical, I prototype a working system in the context of IEEE 802.11n, which is the dominant consumer wireless networking technology today and includes these state-of-the-art RF techniques. Finally, to show that it works, I use my prototype to evaluate the accuracy of the choices made using my techniques. I find that my model accurately predicts packet delivery over hundreds of indoor wireless links in two environments, and that this level of accuracy is

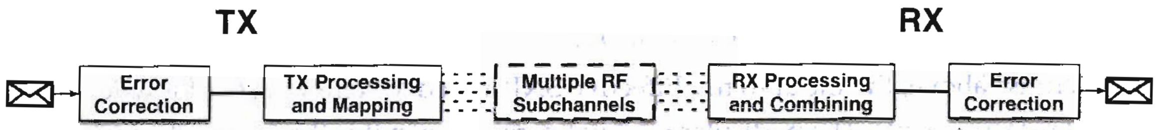


Figure 3.9: Simplified overview of an RF link operating over multiple subchannels.

sufficient to lead to good configurations for many link and network problems.

3.5.1 *Effective SNR-based Model*

The central component in my thesis is a model for packet delivery that uses low-level RF measurements called CSI (see Section 3.5.2 below) to predict packet loss over real wireless channels. To be useful, this model must accurately predict the packet delivery probability for a given physical layer configuration operating over a given channel. It must also simple and practical, so that it can be readily deployed, and cover a wide range of physical layer configurations, so that it can be applied in many settings and for many tasks.

In this thesis, I scope my model to devices that use MIMO and OFDM, which captures the fundamental technological primitives for many current and future networks. In particular, the scope of my model is 802.11n including all the enhancements described in Section 2.1.3. My model is based on the concept of Effective E_b/N_0 developed by Nanda and Rege [78], and described as follows.

Figure 3.9 shows a simplified overview of a link operating over an RF channel that has multiple subchannels, such as MIMO spatial paths or OFDM subcarriers. The transmitter applies error correction to the original data packet, and then processes the coded bitstream and maps the resulting symbols onto the multiple subchannels. The receiver processes the noisy signal to recover the (potentially errored) coded bitstream, and then uses error correction to attempt to recover the original data bits.

The key hypothesis introduced by Nanda and Rege is that error correction—in conjunction with mechanisms like frequency- and spatial-aware interleaving in 802.11n—works to spread the errors caused by faded subchannels across the entire channel. If this assumption holds, the link can be modeled as performing with an aggregate error rate equal to the average error rate across subchannels. This average bit error rate is called the *Effective BER* of the channel, and from it we can compute the *Effective SNR* of the channel. Since the four links displayed in Figure 3.8 have similar error performance, they should have similar Effective SNRs. Then the Effective SNR can be used as a metric of link quality, and hence provide accurate estimates of packet delivery.

3.5.2 *Model Input: Fine-grained RF Measurements*

As described above, the input to my Effective SNR-based system is a set of low-level RF channel measurements. The particular measurements I use in this thesis are called Channel State Information (CSI). For an OFDM link, the CSI comprises the channel gain coefficient (amplitude and phase,[1] see Chapter 2) for each OFDM subcarrier. For an NxM MIMO link, the CSI is an NxM matrix where each entry reflects the channel gain coefficient from one transmit antenna to one receive antenna. For a MIMO-OFDM link such as in 802.11n, the CSI comprises a three-dimensional NxMxS matrix that reflects the NxM MIMO link for each of S subcarriers.

A single comprehensive CSI measurement captures the low-level channel details that enable my model to calculate the Effective SNR for a wide configuration space. I next summarize how these measurements are used.

3.5.3 *Model Output, and how to Apply it*

I describe the model and how it's used in in complete detail in the next chapter, but the basic structure of the model is simple: given (1) a current CSI measurement of the RF channel between transmitter and receiver, and (2) a target physical layer configuration of the transmit and receive NICs, it predicts whether that link will reliably deliver packets in that configuration.

With this simple decision primitive, we can easily build higher layer optimization protocols. These include solutions to all of the problems mentioned in this chapter, such as selecting the best rate, number of spatial streams, or transmit antenna set; whether to use 20 MHz or the entire 40 MHz channel; or choosing the lowest transmit power at which the link supports a particular rate.

Note that I do not try to make predictions in the transition region during which a link changes from lossy to reliable. Predictions there are likely to be variable, and simply knowing when the link starts to work is useful information in practice. For the model output, I define that the link will work, i.e., will reliably deliver packets, if the model predicts ⩾90% packet reception rate. As we will see in this thesis, this system provides good performance across a range of wireless configuration problems.

3.5.4 *Problems Solved*

but you don't "solve" beamforming?

Table 3.1 shows a list of several potential applications of Effective SNR. These cover all the problems described above and range from optimizing various parameters of a single Wi-Fi link, such as the MCS or antenna set used, to coordinating many nodes in a dense wireless

---

[1] Note that in Figure 3.8, I plot only the amplitude as the phase offset does not affect packet delivery for a SISO link (assuming it is properly equalized by the receiver).

Application of Effective SNR	Described in
Bitrate/MCS selection	Chapter 6, Chapter 7
Channel width selection	Chapter 6, Chapter 7
Antenna selection	Chapter 6, Chapter 7
Transmit power control	Chapter 6
Channel selection	Chapter 8
AP selection	Chapter 8
Path selection/BSS selection in WDS	Chapter 8
Interference planning/Spatial ~~reuse~~	
Partial packet recovery/FEC	Bhartia et al. [14]
Beamforming	
Multicast rate selection	

acronyms?

not discussed

So these are speculative? make that clear earlier

Table 3.1: A variety of applications of Effective SNR.

typography error need some white space

Application of CSI	Described in
Mobility classification	Chapter 8
Indoor localization	FILA [123], PinLoc [101], SpinLoc [99]

Table 3.2: A variety of applications of Channel State Information.

network. Additionally, I identify applications that can be implemented by looking at other aspects of the Channel State Information in Table 3.2. These provide useful primitives that can enable systems to adapt behavior based on the location and movement of the user.

what?

Combined, I believe these form the critical building blocks for configuring dense future wireless networks like Wi-Fi Direct. In particular, my Effective SNR model provides the information needed to select rates or configure the network topology among other things. The CSI can be used to supplement these schemes, particularly by using mobility classifica~~tion to determine~~ when a device starts to move and trigger reconfiguration of the wireless network in response. I implement and evaluate many of these applications in the rest of this thesis, several have been investigated by other researchers in follow-on work, and some are left for future research.

not in Table 3.1

which?

You never define "mobility classification" in this chapter or earlier?

3.6 *Summary*

In this chapter I have presented a detailed overview of wireless link and network configuration problems, and the statistics-based and channel-based approaches ~~we take to~~ used ~~solving them~~ today. Generally, statistics are too specific, applying only to a single or a few configurations. Conversely, channel measurements used previously have been too general, not capturing the low-level details of the channel. I then described my channel-based approach, which uses low-level channel measurements of the MIMO and OFDM subchannels

Again I don't agree w/ this distinction

in conjunction with an Effective SNR-based model to provide a way to predict performance over the broad configuration space. In the next chapter, I flesh out this model and how to use it, and argue that it is indeed flexible and has low overhead. In the remainder of the thesis, I will show that my model makes accurate predictions that lead to good choices of operating points in practice for many of the problems I described in this chapter.

3.5 belongs at ~~the start of 3.6~~ Chap 4

You need to describe Nanda & Rege more clearly **before** you start talking about your work.

Eg. their limit is that they would ~~predict~~ calculate the eff SNR from the effective BER & that doesn't work, so you do X instead.

Not at all clear here what X is, since you call it "my Eff SNR" that makes it seem like it is exactly what Nanda & Rege do

I think its best in a thesis ~~not~~ to use ~~abbrev~~ the formal names of conferences & journals
e.g. what is ToN?

Also, not sure the "In" is necessary in In X, 2005

http names shouldn't have periods after them, as its ambiguous & I verify look at the end of those URLs.

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