Physical Concerns for Cross-Layer Prototyping and Wireless Network Experimentation

Ketan Mandke
mandke@ece.utexas.edu

Robert C. Daniels
rdaniels@ece.utexas.edu

Soon-Hyeok Choi
schoi@ece.utexas.edu

Scott M. Nettles
nettles@ece.utexas.edu

Robert W. Heath, Jr.
rheath@ece.utexas.edu

ABSTRACT

The performance of a wireless network protocol is inseparably linked to the physical layer algorithms on which it is built, the hardware used to implement the radio, and the wireless environment in which it operates. This paper identifies three features of wireless networking protocols impacted by these *lower-level* characteristics that are often overlooked or misunderstood by many researchers developing wireless protocols or using testbed-based evaluation methods. These features are temporal scaling, measurement reciprocity, and cross-layer adaptation. Temporal scaling refers to the time resolution with which events, such as broadcast or feedback, occur in the wireless network. This feature is tightly coupled with processing time at the physical layer and time selectivity in the wireless channel. Measurement reciprocity is an assumption used to estimate parameters of the forward link of a bidirectional communication channel, based on observations from the reverse link. This assumption directly depends on the interference properties and hardware symmetry of nodes in a wireless network. System adaptation, based on reciprocity or feedback, inevitably requires careful scrutiny of power and rate control applied to physical wireless devices. This paper also provides recommendations to guide researchers in setting up interesting and useful wireless experiments. Three concerns for wireless experimentation are addressed, namely: ambient interference, RF hardware profiling, and fading properties of the wireless channel. The motivation for this paper stems from experience prototyping and experimenting with Hydra, a wireless cross-layer testbed developed at the University of Texas at Austin.

Categories and Subject Descriptors

C.1.2 [**Network Architecture and Design**]: Wireless Communication

General Terms

Experimentation

Keywords

cross-layer design, wireless prototyping

WiNTECH'07, September 10, 2007, Montréal, Québec, Canada.

1. INTRODUCTION

Recent cross-layer design for wireless networking protocols has yielded significant performance improvements through physical, link, and network layer interaction [1]. One such result, the rate-adaptive medium access control (MAC) protocol RBAR utilizes physical layer (PHY) information [2]. Specifically, RBAR uses signal-to-noise ratio (SNR) to opportunistically adapt data rates to exploit variations in the wireless channel. This protocol exploits only one degree of freedom at the physical layer, namely rate control. Emerging PHY technologies, however, provide a variety of new degrees of freedom, such as multiple antenna systems, ultra-wideband (UWB), and orthogonal frequency division multiplexing(OFDM). As future wireless networking protocols will undoubtedly make use of these emerging technologies through cross-layer design, it is important to understand the impact of the interactions between these physical layer technologies and higher layer protocols.

Realistic evaluation and characterization of these interactions through experimentation provides keen insight into the appropriate abstractions for modeling physical layer processing, RF hardware, and the wireless channel. Testbeds and prototypes are useful tools for evaluating wireless networks and characterizing the behavior of these pieces of the wireless puzzle. Improving models for these physical characteristics of wireless devices will ultimately lead to the design of better cross-layer protocols.

There are numerous wireless prototyping efforts in the literature such as [3–7]. In developing a wireless testbed, physical and MAC layer protocols may be implemented using custom hardware (such as field programmable gate arrays, FPGAs, or application specific integrated circuits, ASICs), general purpose processors (as in software defined radios), or commercial off-the-shelf (COTS) radios. Many wireless network testbeds such as Roofnet [4], ORBIT [5], and MiNT [6] have used COTS radios to investigate ad hoc routing protocols and mobility in wireless networks. Testbeds that implement custom physical layer designs require additional development time and resources, but have the ability to accurately characterize the behavior of PHY algorithms and their interaction with higher layer protocols. Hydra, a wireless testbed developed at the University of Texas at Austin, is such a

This material is based in part upon work supported by the National Science Foundation under grants EIA-0322957, CNS-0435307, and CNS-0626797, the Air Force Research Lab under grant numbers FA8750-06-1-0091, and FA8750-05-1-0246, the Office of Naval Research under grant number N00014-05-1-0169, and the DARPA IT-MANET program, Grant W911NF-07-1-0028.

testbed. Hydra implements PHY and MAC protocols using a completely software-defined protocol architecture. This method of prototyping allows for flexible implementation of cross-layer protocols and provides insight into the interaction between the physical layer and higher layer protocols.

Many wireless network experiments in the literature suffer from inadequate consideration of the cross-layer implications of wireless prototyping. Unlike experiments in wired networking, experimentation with wireless networks requires a deeper understanding of the hardware and algorithms “closer” to the actual physical transmission. In particular, this paper argues that the impacts of physicali layer algorithms and implementation, radio hardware, and characteristics of wireless channels must be addressed when building wireless experiments. These physical concerns also impact the design of wireless networking protocols. We identify three major features of higher layer protocols that are impacted by these physical concerns, namely: temporal scaling, reciprocity, and cross-layer adaptation. The physical features discussed in this paper must be considered in order to effectively design and evaluate wireless networking protocols through simulation, analysis, or experimentation. The motivation for this paper stems from our experience prototyping and experimenting with Hydra.

The remainder of this paper is organized as follows. Section 2 describes the Hydra testbed and the software-defined protocol architecture used to implement its flexible cross-layer algorithms. Section 3 examines cross-layer impacts of physical layer algorithms, along with hardware and channel impairments. Next, in section 4 we provide a set of recommendations to guide researchers in designing more effective wireless experiments. In particular, we discuss some of the considerations that may impact experimental results and how *interesting* wireless scenarios might be set up. Finally, section 5 concludes the paper.

2. HYDRA OVERVIEW

Since our motivation for investigating cross-layer impacts in wireless prototyping stems from our experiences prototyping and experimenting with Hydra, we begin with a description of our testbed. Hydra is a flexible wireless prototype implemented using a general purpose PC and open-source RF hardware, as shown in Figure 1. The PHY, MAC, and network layer protocols for Hydra are implemented entirely in software that runs on a general purpose processor. This software-defined approach allows for a great deal of flexibility in protocol design and allows for tightly coupled cross-layer interaction. Although an FPGA or ASIC implementation would provide faster performance, using a high-level programming language like C++ on a general purpose machine requires less development time and is more amenable to most networking and communciations researchers, who may have little or no experience with such hardware.

Hydra’s software is implemented using two open-source software packages: GNU Radio [8] and Click [9]. These packages allow developers to flexibly implement modular signal processing or packet processing blocks in C++ and connect them together using a simple glue language. The community of users and developers for these software packages is broad, ranging from amateur radio and networking enthusiasts to experienced university and industry researchers.

The RF frontend of Hydra is implemented on an open-

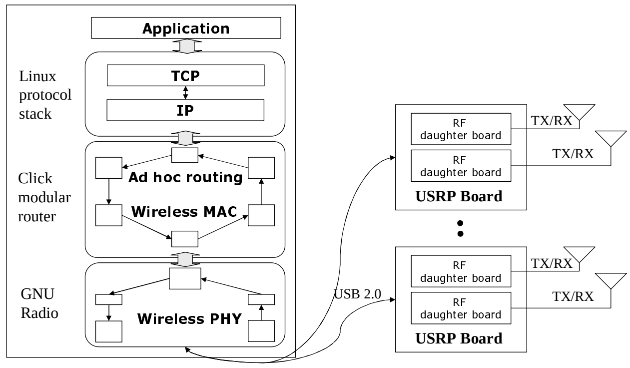

Figure 1: Block diagram of a Hydra node. Each node consists of a general purpose host and a Universal Software Radio Peripheral board [10].

source hardware platform, the Universal Software Radio Peripheral (USRP) [10]. This frequency agile radio platform provides a flexible data and control interface through a USB 2.0 connection, a million gate FPGA, and four high-speed analog-to-digital and digital-to-analog converters (ADCs and DACs). GNU Radio provides an API to operate this RF frontend. The RF hardware also has the capability to support multiple antennas, which we will utilize in experimenting with multiple-input multiple-output (MIMO) systems.

Hydra features an OFDM physical layer based on the IEEE 802.11a standard [11] that is implemented in GNU Radio. This PHY supports multiple data-rates through a combination of various convolutional coding rates and modulation schemes. The MAC layer of Hydra is implemented using the Click modular router [9] and features a variety of random access MAC protocols. Network protocols are also implemented in Click and can interface to the Linux TCP/IP stack to enable end-to-end application layer experiments.

A detailed description of Hydra is available in [3]. A MIMO physical layer and corresponding adaptive MAC protocol are being added to the prototype. We are currently using Hydra to investigate rate adaptive MAC protocols. The concerns addressed in the next section stem from this experience prototyping and experimenting with cross-layers protocols.

3. EFFECTS OF CROSS-LAYER PROTOTYPING

Physical layer processing, hardware impairments, and the wireless environment impact the performance of cross-layer algorithms. In this section, we identify three features of higher layer protocols impacted by these components in practical wireless systems, namely: temporal scaling, reciprocity, and cross-layer adaptation. The physical concerns addressed in this section should be included in the design of all wireless networking prototypes and experiments. Although our experiences prototyping with Hydra motivate this discussion, our results will not be confined to implementation specific issues. Rather, we present more general cross-layer concerns for prototyping and experimenting with wireless network protocols.

As mentioned, we will discuss three general features that impact the performance of higher layer protocols. The temporal scaling feature refers to the time granularity with which events in higher layer protocols occur. We also examine the

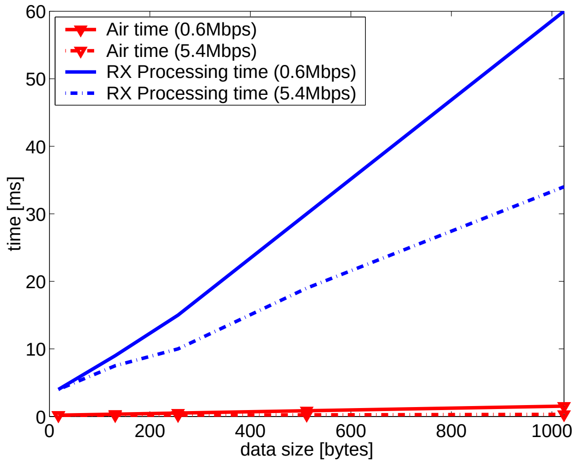

Figure 2: Processing time versus packet length in Hydra.

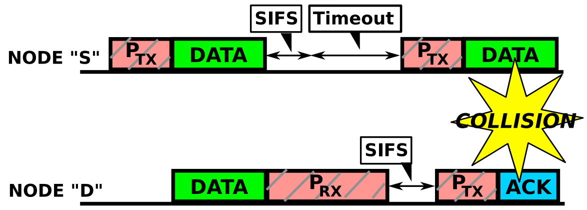

Figure 3: Improper interframe spacing may break MAC protocols.

reciprocity assumption, which assumes that bi-directional wireless links are symmetric. Finally, we discuss the cross-layer impacts of metrics used for adaptation. For example, received signal strength indicator (RSSI) is often used as a metric for indicating link quality, even though it does not account for the impact of interference. A more appropriate metric might be signal-to-interference-and-noise ratio (SINR). The remainder of this section argues that the performance of higher layer protocols are tightly coupled to physical devices and PHY algorithms.

3.1 Temporal Scaling

Temporal scaling is the time scale or granularity with which communication occurs in higher layer protocols. For example, this might refer to the interframe spacing times of a MAC protocol or the periodicity with which broadcast and routing messages are sent by a routing protocol. The temporal scale of cross-layer protocols depends not only on the time required to transmit and receive packets, it also depends on the time-varying characteristics of the channel and the complexity of encoding and decoding waveforms.

When commercial designers implement MAC and PHY protocols for consumer wireless devices, they adhere to strict timing specifications listed in the standards document under which the radio operates. The challenge for these engineers is to design algorithms in hardware with enough speed to satisfy these timing constraints. In designing wireless prototypes, however, researchers do not have to adhere to such standards and timing constraints. Instead, MAC and network protocol design on testbeds is constrained by the processing time of PHY algorithms. Thus, as a matter of practical concern, it is important to understand the complexity and processing time for the physical layer algorithms we wish to use in prototyping.

In most physical layer decoding algorithms, lower rate packets generally have a higher decoding complexity and in most cases are more reliable (i.e. have a lower packet-error rate). Often this processing delay is poorly characterized by higher layers as a constant time process. In Hydra, we profiled the performance of the physical layer and gathered statistics on the processing time for various physical layer decoding algorithms, as shown in Figure 2. This figure shows how the processing time required for two data rates, 0.6 Mbps and 5.4 Mbps, increases with packet length in bytes. The figure also shows how, in Hydra, the actual air time for transmission of the physical layer waveform is significantly less than the receive processing time.

Since processing time for Hydra is dominated by the complexity of the Viterbi decoding algorithm for our error-control coding, processing time scales linearly with packet length. Although the particular scaling relationship between processing time and packet length will be implementation specific, in general processing time will increase for longer packets. This experiment provided us with the information necessary to appropriately tune temporal scaling issues in our MAC protocol. Improper interframe spacings can cause catastrophic failure in the MAC layer as shown in Figure 3. This figure shows a hypothetical trace of two nodes communicating. After node S transmits a data waveform, it will wait for a short interframe spacing (SIFS) time plus some timeout value for an acknowledgement (ACK). If a timeout occurs, node S will retransmit its data waveform. If P_{RX}, the receive processing time at node D, is too long, its ACK message may collide with the retransmission from node S. This retransmission policy will cause catastrophic failure. In order to properly tune such SIFS and timeout values, the MAC must account for processing delays in the physical layer.

Although the results presented thus far have been for a software-defined radio, they are still relevant to real-time systems, where processing time in the physical layer is less than the air time of the waveform. Even in real-time systems, which might be implemented in FPGAs or silicon, processing time in the physical layer still scales with the datarate and length of packets. Thus, MAC protocols should still be aware of the processing time required by PHY algorithms.

One of the main purposes of Hydra is to investigate cross-layer protocols that utilize side information. In particular, we are examining adaptive protocols that use feedback and other mechanisms for sharing side information. The opportunistic gain achieved by these types of cross-layer protocols depends on the rate of adaptation and feedback used in the system. The time-scale over which adaptation and feedback can be done depends on the time-varying statistics of the channel, in particular the time over which the channel is statistically stationary, known as the coherence time. In cross-layer algorithms where side information is utilized, overestimating this parameter can cause imperfect or stale side information to be used for adaptation. Underestimating this parameter can lead to unnecessary communication overhead for measuring or feedback of side information.

Coherence time depends on the time-varying nature of the wireless channel. Mobility impacts the slow variations in the first order statistics of the wireless channel. However, rapid fluctuations in the channel, which determine the statistics used to approximate coherence time, are a result of Doppler

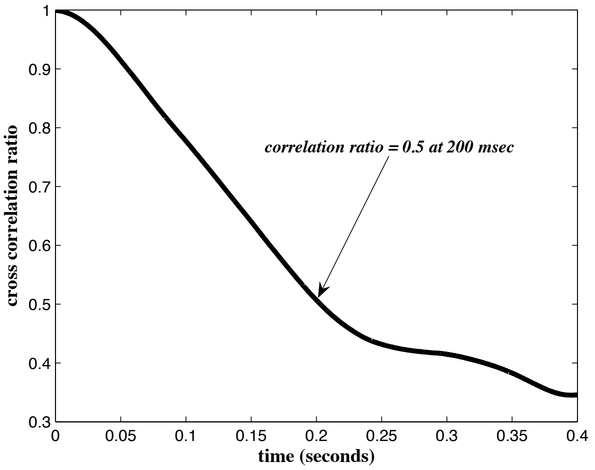

Figure 4: Cross-correlation statistics in an indoor office setting at 2.5 GHz, collected using Hydra. Coherence time is approximately 200 $msec$.

in the environment. In this context, Doppler is the effect of relative motion throughout the wireless environment. Since coherence time is difficult to model and can be environment specific, it is important to characterize this parameter in the specific environment used in a wireless experiment. Figure 4 shows some preliminary data collected to estimate coherence time in the indoor office setting of our fourth floor laboratory. Coherence time is defined in [12] as the time at which the cross-correlation statistics of the channel fall below 0.5. Thus, Figure 4 shows the coherence time in this indoor environment is approximately 200 $msec$. Consider a hypothetical network layer protocol which attempts to reconfigure its routing algorithm based on channel information gathered from the physcial layer. Depending on the time scale of the protocol, channel information might become uncorrelated, or *stale*, before the protocol has a chance to utilize it, which might result in bad routing decisions.

3.2 Measurement Reciprocity

Measurement reciprocity is an assumption used to estimate parameters of the forward link of a bidirectional communication channel, based on observations from the reverse link. Many cross layer protocols use reciprocity to gather side information about the wireless link to a potential destination. For example, in [13], the authors propose a power control protocol for ad hoc networks that adapts power "to the lowest value which keeps the network connected." This adaptation mechanism gathers information about the received power of broadcast messages from its neighbors. By using the reciprocity assumption, the protocol then makes decisions about the appropriate power level required to communicate to its neighbors. Our experience with Hydra has shown that this assumption does not always hold true. Two of the main causes for the asymmetric nature of wireless channels are intereference and variance in RF hardware.

Consider the configuration of a sender node S and destination node D with some interferer shown in Figure 5. Node S may attempt to estimate its channel to node D by overhearing transmissions from this destination node. The power of interference from node I decays according to the pathloss

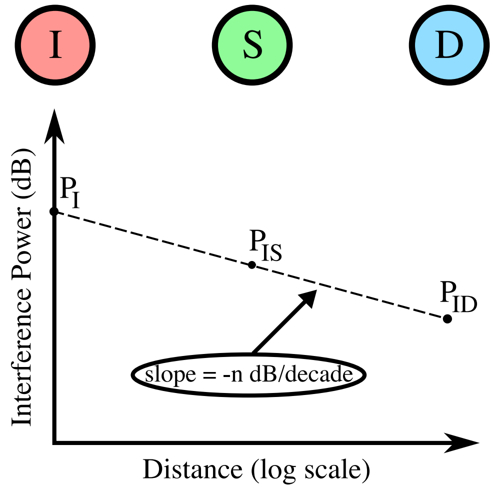

Figure 5: Node S attempts to estimate its channel to node D through reciprocity in the presence of asymmetric interference from node I.

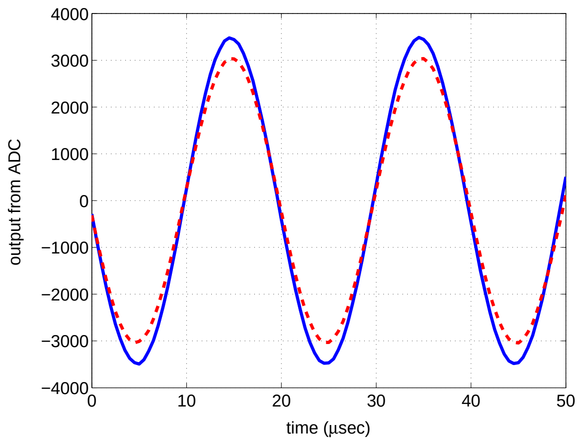

Figure 6: Asymmetric hardware between two Hydra nodes. In-phase component of forward and reverse link represented by solid and dashed line repectively.

metric n, which models the large-scale propagation loss in a particular environment. Thus the interference power at the sender, P_{IS}, is different from the interference power at the destination, P_{ID}.

The presence of this asymmetric interference, even if it is low powered or far away, can cause node S to get a noisy estimate of its channel to node D. This incorrect side information can impact the performance of adaptation schemes. For example, if node S employed a reciprocity-based rate-adaptive scheme that adapts rate to SNR, it may experience interference which does not impact the quality of the wireless link at node D as severely. This can cause node S to make overly conservative rate decisions. Also, in multiple antenna systems which use beamforming, a MIMO method for adapting to the structure of a particular realization of the wireless channel, such incorrect side information can lead to severe problems which might even be worse than not adapting at all.

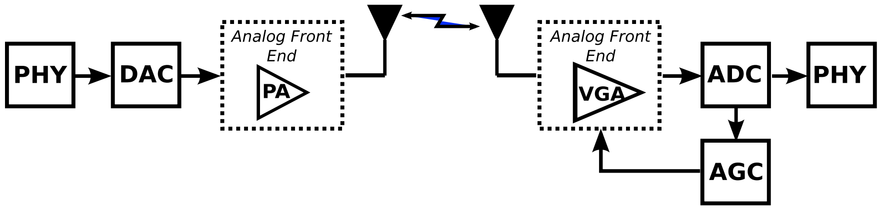

Figure 7: Block diagram of physical transmit and receive chains.

Variations in RF hardware also contribute to the asymmetry of communication links. Physical characteristics for hardware such as noise figure, linearity, and frequency response can vary from component to component. These variances create asymmetries between different nodes and different transmit/receive chains. Thus a signal sent from one node to another is different than the signal sent in the reverse direction. An experiment with Hydra shows an example of this type of asymmetry in a real system. In this experiment, two Hydra nodes are connected directly with a cable, isolating the signal from any asymmetries in the wireless channel. One prototype node transmits a complex sinusoid while the other receives the signal. This is repeated in the reverse direction. The in-phase component of the received signal at both nodes, shown in Figure 6, indicates that the power received at each node is different, even though both nodes used the exact same hardware and software configuration. A power control algorithm that agressively tries to minimize the transmit power needed to maintain connectivity would suffer dramatically from this type of asymmetry, as it would often make incorrect power control decisions.

3.3 Cross-layer Adaptation

All cross-layer protocols seek to adapt some behavior or functionality at a given protocol layer based on the information usually abstracted to another layer. This adaptation may exploit degrees of freedom available at a lower layer. We examine the cross-layer impacts of two such degrees of freedom available at the physical layer, namely: power and rate control. In this section, we also argue that MIMO-mode selection should not be treated as just another mechanism for rate control. The results presented here come from experimentation with power and rate control in Hydra.

3.3.1 Power Control

Most power control algorithms in the literature assume that increasing transmit power will improve SNR at the receiver, and thus improve overall signal quality to decrease packet-error rate. As shown in Figure 7, in all wireless devices, the signal being transmitted by the RF hardware must pass through a power amplifier (PA) which has some non-linear characteristics. While operating in the linear range of the PA, increasing transmit power will improve signal quality as expected. However, operating in the non-linear range of the PA will cause non-linear effects such as clipping or smoothing which can dramatically degrade the performance of PHY algorithms. Higher layer protocols which employ power control should be aware of the linear range of this amplifier and know that increasing transmit power beyond this range can degrade performance.

In most wireless devices, an automatic gain control (AGC) is implemented in the receive chain, as shown in Figure 7. The AGC automatically modifies a programmable or voltage-controlled gain amplifier (VGA) in the receive chain to prevent overloading of the analog-to-digital converter or to improve the dynamic range of the signal. The AGC also impacts the performance of cross-layer algorithms that adapt power. Consider a power control algorithm where a transmitter attempts to increase its transmit power to improve signal quality. A receiver with AGC might automatically change the received gain, and thus the effective received power. This means that a power control algorithm cannot adjust signal quality by controlling transmit power alone. A power control algorithm must also be aware of how the AGC is altering the received signal.

3.3.2 Rate Control

Physical layer (PHY) protocols provide multiple rates usually through a combination of various coding and modulation schemes. Lower rates are designed to be more robust to bit-errors (i.e. have lower bit-error rates, BER) and thus are more reliable. Many cross-layer protocols depend on this rate-reliability tradeoff in their design; for example, control packets in MAC protocols and broadcast packets in network protocols are often sent at the lowest data rate to increase reliability. The following examples illustrate our claim that it is important for cross-layer protocols to be aware of the impact of rate and mode selection on reliability; and how impairments in RF hardware and the wireless channel can degrade the rate-reliability tradeoff in real systems.

Frequency drift causes the carrier frequency of a system to drift about its desired value and is sometimes referred to as phase noise. A packet transmitted at a lower rate requires a longer waveform which can suffer from more drift. In systems with a large amount of phase noise, this drift can cause dramatic errors at the end of long waveforms. Thus, sending a long packet at a lower rate (which increases the size of its waveform) does not always ensure that the communication will be more reliable. The ability to track and compensate for this frequency drift depends a great deal on the particular tracking algorithm used by the PHY and the amount of phase noise introduced by the RF hardware. The main impact of phase noise to a higher layer protocol is that this impairment degrades the rate-reliability tradeoff.

Another impairment that impacts the rate-reliability tradeoff comes from the wireless channel itself. In multiple antenna systems, MIMO space-time algorithms can be designed to utilize the multiple antennas to improve reliability or to increase rate through space-time coding or spatial-multiplexing techniques respectively. In channels where SNR is high it may be desirable to increase the data rate of the system, i.e. through spatial-multiplexing. However, spatial-multiplexing algorithms only perform well in certain types of wireless channels with *good* spatial structure. This means that increasing the rate of a MIMO system through spatial multiplexing in a channel with *bad* spatial structure will result in a dramatic decrease in reliability. It is important for cross-layer algorithms wishing to adapt between different MIMO-modes to be aware of traditional metrics such as SNR as well as the spatial structure of the channel.

Our final example deals with orthogonal frequency division multiplexing and illustrates the impact of frequency-selectivity on cross-layer adaptation. Wider bandwidth wireless channels experience frequency-selectivity that can result in a dispersive channel which corrupts transmitted waveforms. OFDM physical layer implementations have become increasingly popular in wireless networks due to their tolerance to such dispersive wireless channels. OFDM divides a frequency-selective channel into a set of parallel frequency-flat subchannels and multiplexes data over these subchannels in the frequency domain. This allows the frequency-selectivity of the wireless channel to effectively be treated as a set of simpler *non-dispersive* parallel subchannels. Adaptation for current OFDM physical layers is not based on a frequency-selective metric. Instead, adaptation in frequency-selective channels is often based on time-averaged or, equivalently, frequency-averaged metrics. These adaptation algorithms may break down in frequency-selective channels. Determining the proper adaptive algorithm to account for coding and modulation in a frequency selective channel is still an open problem. Practical metrics for adaptation in frequency-selective channels can be investigated through experimentation on cross-layer prototypes, such as Hydra.

4. RECOMMENDATIONS FOR WIRELESS EXPERIMENTS

In this section we provide recommendations for experimenting with wireless testbeds. Specifically, we identify three physical features of wireless devices and the wireless environment that should be addressed when using testbed-based evaluation methods. These physical features of devices and channels must be properly measured and characterized by experimenters, regardless of whether they are using COTS radios or custom-designed hardware. In order to design *interesting* wireless experiments, we argue that it is important to characterize certain physical features of the specific hardware and environment used in the experiment, namely: ambient interference, RF hardware impairments, and fading properties of wireless channel. As discussed in the last section, making incorrect assumptions about the characteristics of these physical features can have cross-layer consequences.

4.1 Ambient Interference

When setting up a wireless experiment, it is important to consider the RF band of operation. In choosing the electromagnetic spectrum in which to operate, experimenters must consider the availability of spectrum and the possible presence of interferers. National entities control spectrum allocation limiting the frequency of operation for wireless experimentation. In most nations the bandwidth that is legally used for academic experiments (without specific experimental licenses) is constrained to unlicensed spectrum. For example, in the United States the Federal Communication Commission (FCC) maintains regulations for unlicensed spectrum in its Part 15 guidelines, allowing unlicensed operation in the $902-928$ MHz, $2400-2483.5$ MHz, $5725-5850$ MHz, $57-64$ GHz, and $92-95$ GHz bands.

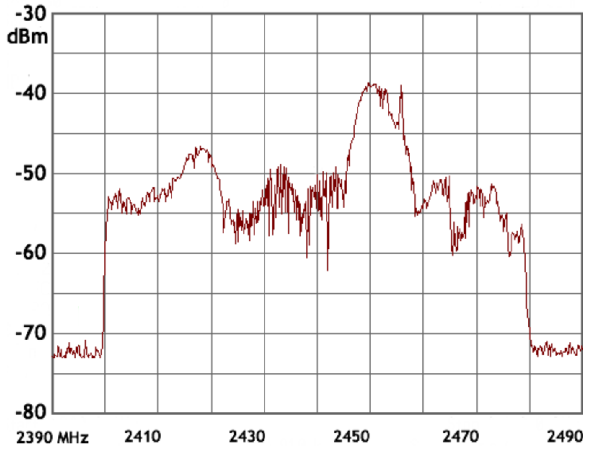

Figure 8: 2.4 GHz **ambient interference observed**

Many commercial products including Wi-Fi, bluetooth, and cordless phones operate in the unlicensed 2.4 GHz and 5 GHz bands as allowed under the FCC Part 15 guidelines. Experimentation within these frequencies must carefully observe interference from commercial systems. Interference from these non-cooperative wireless devices limits the integrity of experiments primarily by increasing the probability of packet-errors. Interference also contributes to errors in estimating parameters such as RSSI and SINR, which might be used by higher layers. Finally, uncontrolled interference is difficult to characterize temporally, thereby making experimental results very dependent on the particular behavior of an interferer.

Experiments performed with the Hydra prototype utilize the 2.4 GHz band. Figure 8 shows the power-spectrum of this RF band as measured in our fourth floor laboratory. This figure shows that the 2.4 GHz spectrum in our laboratory is saturated with traffic from the campus' wireless internet access points. In order to avoid this interference source, experiments were conducted at the edge of this unlicensed band. An alternative and more costly interference avoidance technique would be to install shielding material or remove interference sources around the experiment. Experimenters must be careful, however, that such interference avoidance methods do not fundamentally change the propagation characteristics of the wireless channel.

4.2 RF Hardware Profiling

The RF hardware of a wireless device is composed of two principal components: antennas and the analog front end. The antennas provide the interface between the wireless medium and the analog front end. This analog front end modulates and demodulates a signal to and from the operating carrier frequency so that it can be processed by physical layer algorithms. We discuss two features of these hardware components that should be characterized before experimentation, namely: system loss and signal distortion. Signal loss is a characteristic of the hardware that describes static power

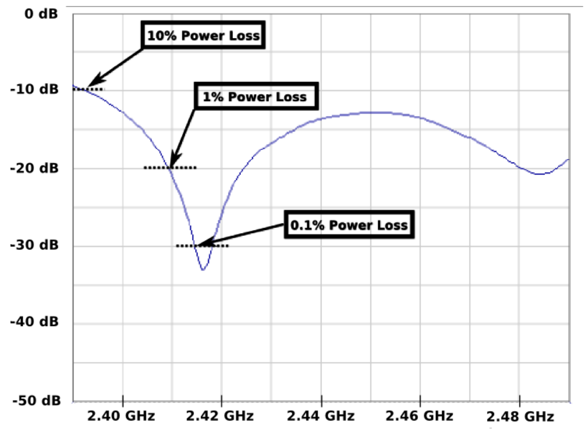

Figure 9: S_{11} measurements for a 2.4 GHz antenna

loss. Signal distortion, however, characterizes the time and frequency dependent power loss in the hardware.

4.2.1 System Loss

Theoretical and simulated results often ignore the system loss associated with implementation in real hardware. This loss in power can contribute to a gap between theoretical and observed link performance. For example, the authors of [14] propose a networking protocol which makes geographic assumptions based on the range of wireless transmissions. The range of transmission not only depends on the propagation characteristics of the channel, but also the loss experienced by the hardware (i.e. system loss). Incorrectly characterizing system loss will cause inaccurate range values, leading to improperly constructed experiments. System loss can be measured in antennas using S_{11} reflection coefficient measurements. The system loss associated with the analog front end requires a detailed analysis of hardware components and is usually provided by manufacturers. This characteristic in the antenna is symmetric for transmit and receive directions, but the analog front end is fundamentally different for each direction, leading to asymmetry in the system loss for communication.

4.2.2 Signal Distortion

Signal distortion can be observed in both the analog front end and antennas. This distortion is frequency dependent and non-linear. A detailed discussion of distortion in the analog front end can be found in [15]. As with system loss, profiling the signal distortion of the analog front end requires detailed measurement procedures and is usually provided by manufacturers. Profiling the signal distortion of antennas can aid in selecting the right antennas for experimentation. Investigators often naively choose antennas by purchasing off-the-shelf components rated at the desired operating frequency. By not profiling the reflection coefficient of antennas over the entire operating bandwidth, experimenters are unwisely making the assumption that antennas radiate the same energy at all frequencies without loss. Consider the S_{11} measurements in Figure 9 of an off-the-shelf antenna sold for operation in the 2.4 GHz band. This figure shows the frequency-dependent power loss of this particular antenna.

Frequency selectivity in the power loss of the antennas results in consistent signal distortion that negatively impacts system performance. Moreover, this frequency selectivity can lead to improper adaptation since the system may misidentify the signal distortion of the antenna as frequency selectivity in the channel.

Practical antennas are also spatially selective, meaning they do not radiate or receive energy equally in all directions. Investigators must be careful to choose radiation patterns that make sense for the topology of the experiment they are conducting. For example, using directional antennas in a network experiment can present unexpected behavior if the experiment was designed for omni-directional antennas.

f_c	T_c **in office**	T_c **in suburban outdoor**
900 MHz	200 ms	20 ms
2.4 GHz	300 ms	N/A
5.0 GHz	150 ms	N/A

Table 1: Approximate channel coherence time for office and suburban outdoor environments compiled using measurements from [16–18]

f_c	B_c **range for office**	B_c **range** for suburban outdoor
900 MHz	10 MHz to 20 MHz	500 kHz to 1 MHz
2.4 GHz	3 MHz to 10 MHz	N/A
5.0 GHz	4 MHz to 20 MHz	N/A

Table 2: Approximate bandwidth range for frequency selective fading in office and suburban outdoor environments compiled using measurements from [16–18]

4.3 Fading Properties of Wireless Channels

Fading refers to the frequency and temporal selectivity of wireless channels. This paper has discussed some of the impacts of fading on higher layer protocols. Here, we provide approximate guidelines for how these fading channels can be manufactured for wireless experiments. It is important to understand that fading in the wireless channel has a complex relationship with carrier frequency and system bandwidth. Fading can also depend a great deal on the particular topology and mobility in a specific environment. Although the results presented in this section can serve as a guideline for fading in a particular wireless experiment, it is important to characterize the actual fading properties through careful measurement.

In the wireless environment, a propagated signal can constructively and destructively interfere with itself to create the effective wireless channel. Since the environment and wireless devices are not stationary, this channel will be time-varying. Higher mobility in the wireless environment increases the speed at which the effective channel changes and correspondingly decreases its coherence time, T_c (an approximate measure of how long the channel is static). Coherence time depends on mobility in the wireless channel and on the operating frequency, f_c. Table 1 gives some typical values for T_c in office and suburban outdoor environments at 900 MHz, 2.4 GHz, and 5.0 GHz. In section 3, our measurements for coherence time, obtained through experimenting with Hydra, showed that T_c in our indoor office setting at 2.4 GHz was approximately 200 ms. Although our experimental results are consistent with the measurements presented in Table 1, they are not identical because of the very scenario-specific nature of coherence time measurements.

Frequency selectivity occurs when multiple delayed and attenuated reflections of the transmitted signal arrive at the receiver at intervals exceeding the sample time. This causes the response of the wireless channel to vary over the signal's bandwidth. Wider bandwidth systems have smaller sample times and thus have more frequency selectivity. This is characterized as a smaller coherence bandwidth, B_c, which is an approximate measure of the bandwidth over which the channel can be considered static. Table 2 gives some typical values for B_c in office and suburban outdoor environments at 900 MHz, 2.4 GHz, and 5.0 GHz.

Here, we provide a sample wireless experiment to evaluate the performance of an adaptive cross-layer protocol based on the measured results in Tables 1 and 2. Suppose this hypothetical protocol adapts the rate of each subchannel in an OFDM system based on the frequency selective response of the wireless link. To evaluate such a protocol, we would like our experiment to test the protocol over a frequency selective channel, perhaps operating in the unlicensed 2.4 GHz band. Table 2 shows that in order to observe a frequency selective channel at 2.4 GHz our physical layer must operate over a bandwidth of approximately 10 MHz. If our adaptive scheme requires feedback, it must employ a MAC protocol which enables this feature. In addition, the time required to feedback and adapt to variations in the channel should be less than the coherence time of the channel. If the experiment is performed in a typical office setting, then the total time required for feedback and communication, including processing time, should be less than approximately 300 ms, as shown in Table 1. This example illustrates how experimenters might use these tables as a rule-of-thumb to design *interesting* scenarios for their wireless experiments. Because of the scenario-specific nature of these fading properties, we stress that it is important to characterize the particular wireless environment for an experiment through careful measurement.

5. CONCLUSION

Cross-layer wireless design offers significant improvements over traditional layered protocol design [1]. Unfortunately, the mixture of layers often leads to unforeseen interactions between upper and lower layer protocols. Prototypes and testbeds are useful tools for studying these interdependencies. In general, prototypes force researchers to consider the impact of PHY algorithms, hardware impairments, and characteristics of the wireless channel. We identified three features of higher layer protocols which can be impacted by these physical characteristics, namely: temporal scaling, reciprocity, and cross-layer adaptation. As testbed-based evaluation of wireless networking protocols becomes more prevelant, it is important to understand the impacts of these physical concerns. In particular, we argue that it is important for experimenters to measure and characterize ambient interference, profile RF hardware, and measure fading properties of the wireless channel. In our experience prototyping Hydra, we have observed that inadequate consideration of these issues can significantly impact the performance of higher layer protocols and our ability to conduct useful experiments.

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