Illinois Wireless Wind Tunnel: A Testbed for Experimental Evaluation of Wireless Networks

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Preface: This paper describes a new project at the University of Illinois at Urbana-Champaign. As such, most ideas in this paper are at an early stage of development.

1. INTRODUCTION

Wireless networking has grown in popularity in recent years. Motivated by the many applications of wireless networks, the research community has developed, and continues to develop, many protocols for wireless networks. This paper addresses the development of a facility for experimental evaluation of protocols for wireless networks. Today, evaluation of wireless protocols, and comparison with competing protocols, is typically performed by means of simulations using tools such as ns-2, Opnet, or Qualnet. Simulations, although useful, have their limitations, and often experimental testbeds are necessary for accurate protocol evaluation. Many researchers agree with this observation [9], and many testbeds for evaluating wireless protocols have been proposed in the past. The previously developed testbeds typically have one or more of the following shortcomings:

- Lack of repeatability: For practical reasons, devices used in wireless testbeds operate in the Industrial, Scientific and Medical (ISM) bands. For instance, IEEE 802.11 and Bluetooth devices operate in the ISM bands. Performance measurements on such testbeds are affected by interference from other devices operating in the ISM bands, such as cordless telephones and microwave ovens, and indeed other 802.11 and Bluetooth devices beyond the experimenter's control. Such interference makes it difficult to perform repeatable experiments. Repeatability is an important feature for experimentation, and in most other disciplines (such as physics), an experimental result is often considered invalid unless it can be reproduced.

- Lack of control on many parameters: This is an issue that relates to the above lack of repeatability. The underlying cause for the lack of repeatability is not the presence of interference from other sources. In fact, elimination of such interference is not desired, since real systems do have to operate in presence of interference. The main concern is the lack of control on the interference. The interference level and pattern is beyond the experimenter's control, leading to two problems: (a) as mentioned above, a lack of repeatability, and (b) inability to perform controlled experiments under different levels of interference from unwanted sources. Other parameters beyond an experimenter's control in existing testbeds include reflections from mobile objects (e.g., cars or people), since these mobile objects are typically not under an experimenter's control.

  The ability to control parameters of interest is important to allow comparative evaluation of protocols. For instance, if we can recreate identical mobility patterns for objects in the environment (such as cars), then it would be possible to realistically compare performance of two different protocols. This would also allow use of benchmarks for comparison of wireless protocols. In many disciplines, benchmarks have served a critical role by allowing quantitative comparisons of competing solutions (e.g., the SPEC benchmarks for computer performance). A benchmark for wireless protocol evaluation would specify parameters such as traffic patterns, mobility of hosts within the network of interest, as well as location of objects that serve as obstructions, interference from unwanted sources, etc. The ability to control the various parameters then implies that even if two different protocols were to be evaluated against a given benchmark at very different points of time, their results can still be compared meaningfully.

- Use of approximate models of the channel: Since the previous testbeds typically either simulate or emulate the actual network, a model of the channel behavior needs to be provided as input the simulation/emulation engine. This input may either in the form of a simple mathematical construct or a trace based on actual measurements in a real environment. This approach is not always adequate for accurate evaluation of the wireless channel, particularly when broadcast communication is considered. While physical layer models for the channel between pairs of hosts in the networks are reasonably well-understood, models for the effective channel seen by the higher layers in the network are not well-understood. Some models, such as the two-state Markov model, are in common use, but these do not always capture reality very well [10]. Such error in

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modeling can result in significant deviations between simulation results and results from an implemented system.

As noted earlier, many wireless testbeds have been developed previously. For instance, White et al. [16] suggest that, to avoid unwanted interference, the tests should be performed in a wireless channel that is not in use by other devices in the vicinity of the experimental testbed. They also suggest that to ensure repeatability of mobility patterns the mobile hosts should be installed on objects with predictable mobility – for instance, they suggest using city buses for this purpose, since the buses follow a fixed schedule every day. We do not believe that the above solutions are adequate. When operating in the ISM bands, in typical environments, it is rather difficult to ensure that uncontrolled interference will not occur. Also, objects such as city buses are beyond the experimenter's control. Kaba and Raichle [5] propose an alternative approach wherein wireless links are essentially replaced by cables (while still using the wireless devices), allowing complete control on the network topology. However, this approach lacks the ability to measure impact of certain realistic wireless channel characteristics.

Judd and Steenkiste [4] improve on the approach of Kaba and Raichle, by introducing an emulator that can emulate different channel behaviors, using path loss models specified to the emulation controller. Most recently, Raychoudhury et al. [11] have initiated a project called ORBIT with the goals of developing a large-scale testbed for experimental evaluation of wireless networks. Among the past work, the ORBIT project [11] and the project by Judd and Steenkiste [4] come closest to our goals. Our approach, however, is different and complementary to that taken in the ORBIT project, and can potentially be integrated with the other solutions.

The proposed testbed, named *Illinois Wireless Wind Tunnel* (`iWWT`) is motivated by the shortcomings in many existing testbeds. The name Wireless Wind Tunnel is meant to draw an analogy with the "wind tunnels" used for evaluating aerodynamic properties of aircrafts. This analogy is pertinent along two dimensions:

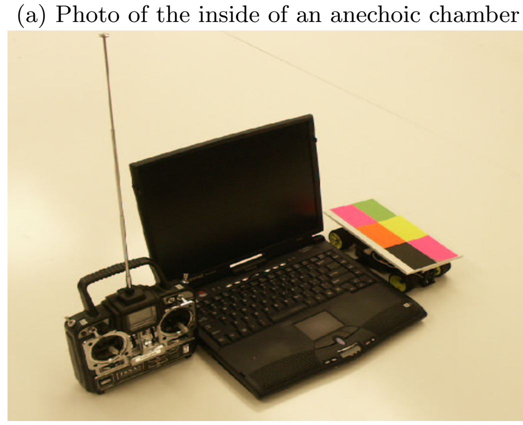
- In aerodynamic testing, since it is often impractical to use a full-scale aircraft, a "scaled model" of the aircraft is instead used. Analogously, since the testbed environment is physically small compared to the physical scale of many wireless networks, we argue that it is not always feasible to evaluate a wireless network in a "full scale" environment, and "scaling" is necessary for practical measurements. For instance, evaluation of a network of roof-top radios would be difficult to perform in an indoor testbed since the distances between the roof-top radios will exceed the physical size of our testbed. Similarly, in the testbed environment, it is not practical to have hosts move at realistic speeds. With this motivation, the Illinois Wireless Wind Tunnel (`iWWT`) will enable "scaling" of the wireless environment. Achieving such scaling is a rather difficult problem, as elaborated later.
- Wind tunnels used for aerodynamic testing can fully control the parameters affecting the performance of the tested aircraft. Analogously, a goal of the Illinois Wireless Wind Tunnel is to exercise full control on the parameters that affect measured performance of wireless networks.

The rest of the paper describes our approach for the implementation of `iWWT`.

2. COMPONENTS OF THE ILLINOIS WIRELESS WIND TUNNEL

The `iWWT` testbed will be implemented in an electromagnetic *anechoic chamber* (Figure 1(a) shows picture of an anechoic chamber). An anechoic chamber is a shielded structure, with two important properties: (a) shielding prevents sources external to the chamber from interfering with reception at hosts within the chamber; and (b) the anechoic chamber is lined internally with absorbing foam panels (egg-crated foam impregnated with carbon to create an electromagnetically lossy material), which reflect minimal energy. With the second property, the walls of the chamber become essentially "invisible" to the devices inside the chamber.

(a) Photo of the inside of an anechoic chamber



(b) RC car, remote control and computer for executing the control loop

Figure 1: Anechoic chamber, and remote-controlled (RC) car

The `iWWT` will include the following components within the anechoic chamber:

- Wireless hosts: Hosts in the network under consideration will either be static or mobile. Mobile hosts will be implemented using remote-controlled (RC) cars [8] carrying wireless devices. There is a constraint on the weight of devices carried by the remote-controlled cars, limiting mobility to relatively small devices. Considering this constraint, we will use two types of devices in the `iWWT`: (a) Lightweight laptops or PDAs (a test with the remote-controlled cars showed that the cars can carry devices under 2 pounds). (b) MICA Motes or similar devices. MICA Motes have the benefit of being more programmable (e.g., the medium access control (MAC) protocol can be modified), whereas the laptops can support heavy-weight protocols and applications.

- Obstructions: As elaborated later, suitable obstructions to wireless transmissions will be introduced in the `iWWT` to mimic similar obstructions in real environments. The obstructions will be designed to introduce effects such as scattering and multipath in a controlled manner.

- Interferers: The anechoic chamber will shield the testbed from external interference. Since real networks do experience interference by unwanted sources (e.g., cordless phones), we will incorporate interferers in our testbed. To model such interferers, transmitters will be deployed at several places in the anechoic chamber. The interference introduced by these devices will be under the control of the experimenter.

- Remote-Controlled (RC) Cars: A remote-controlled car [8] is shown in Figure 1(b). The motion of each RC car in the `iWWT` testbed will be controlled by signals it receives from the corresponding remote control unit. The remote control unit will receive commands from a microcontroller. In turn, the microcontroller will receive commands from a computer (laptop in our testbed) via the serial port. This architecture allows for integration of a diverse set of approaches for location tracking. The controller unit can track the location of the mobile using different techniques, such as triangulation of wireless signals, or by video cameras, or by using mouse-like devices on the mobile units. The `iWWT` testbed can also serve as an environment for comparative evaluation of such tracking techniques as well.

The objective of the Illinois Wireless Wind Tunnel project is to facilitate the evaluation of protocols for wireless networks (for instance, the testbed will be used to evaluate power control protocols, and protocols for reconfigurable antennas). However, designing the `iWWT` in itself is a challenging endeavor, since the wind tunnel calls for *scaling* of the wireless environment that provides realistic measurements. In the rest of the paper, we discuss preliminary ideas on implementing a scaled wireless world.

3. CREATING REALISTIC ENVIRONMENTS

Our goal is to perform realistic evaluations of wireless networks in the `iWWT`. The physical size of the `iWWT` environment is likely to be orders of magnitude smaller than the space occupied by the real networks. Thus, the physical size of the network needs to be scaled down in the testbed. This can affect the channel characteristics seen by the hosts, unless additional precautions are taken, as discussed below.

3.1 Channel Behavior

In a mobile wireless environment, a variety of modes of propagation through the environment can cause significant variations in the channel between the hosts in the network. Consider any one transmitter (Tx) and receiver (Rx) pair, and, for simplicity, assume that there is only one antenna each at Tx and Rx, so that the channel connecting them is one dimensional[1]. Further suppose that there are a total of N paths connecting the Tx and Rx, given the current locations of Tx and Rx. Let the n-th path have amplitude gain β_n and delay τ_n. The delay of τ_n introduces a carrier phase shift, ϕ_n, which is given by the equation below, where f_c denotes the carrier frequency and κ denotes the phase shift introduced by reflectors.

$$\phi_n = -2\pi f_c \tau_n + \kappa \qquad (1)$$

As the locations of Tx, Rx, or objects in the environment change with time due to movement, the channel becomes a time-varying channel. The channel variations can be broadly separated into two scales:

- *Short-term channel variations:* These variations are caused by movements of the order of the carrier wavelength λ_c. Over such short movements of objects, the multipath characteristics can be assumed to be approximately constant [14] (i.e., the number of paths N, and amplitude gains β_n remain approximately constant), and the channel variations are primarily due to changes in the phases ϕ_n. Movements in space of the order of a wavelength cause changes in τ_n of the order of $1/f_c$, which in turn cause changes in ϕ_n of the order of 2π (see Equation 1). These phase changes in the multipath signals can combine to yield rapid variations in the instantaneous channel gain (resulting in variations in received signal amplitude), the maximum rate of variations being equal to the Doppler frequency $f_{\max} = v/\lambda_c$, where v is the speed of movement.

  Modeling the phases ϕ_n as independent uniform random variables over $[0, 2\pi]$, it can be easily shown that the *average* power gain G is given by the sum of the squares of the path amplitude gains, that is, $G = \sum_n \beta_n^2$. Since β_n's remain approximately constant for movements of the order of a wavelength, *average* gain G also remains roughly constant. Thus,

[1]The scaling methods described in this paper can be extended to multiantenna systems where the channel is described by a matrix.

with short-term channel variations, although the *average* gain may remain constant, the *instantaneous* gain can change rapidly with time.

- *Long-term channel variations:* These variations result from a changing multipath profile as a mobile host moves over distances of the order of the average distance between objects (such as walls) in the environment. Such large scale movements result in significant changes in gain G. Long-term variations can be further split into two components as $G = \bar{G}(d) \,.\, S$, where d is the distance between Tx and Rx. The term $\bar{G}(d)$ is a monotonically decreasing function of d that represents the *median gain* of the channel (which is the inverse of the *path loss*). The term S is the residual non-monotonic variation of the G with location and is termed *shadowing*. A commonly used model for $\bar{G}(d)$ is of the form $K\, d^{-\nu}$, where ν is the path loss exponent, and K is a constant.

Different mechanisms need to be used to reproduce the short-term and long-term channel variations within the "scaled" `iWWT` environment. Specifically, the discussion above motivates three types of *scaling* mechanisms (albeit inter-related) that are needed to achieve the goal of realistically evaluating wireless networks in the `iWWT`:

- *Scaling transmit power:* The wireless devices in the `iWWT` may be orders of magnitude closer than in the real environment in which the wireless network will operate. Thus, to maintain the same network "connectivity" and interference patterns as in the original environment, the power "footprints" of the hosts in the network needs to be scaled down appropriately. This scaling can be accomplished by simply scaling down the transmit powers (as elaborated in Section 3.2).
- *Scaling for long-term channel variations:* The frequency of the long-term variations (captured by variations in gain G) is governed by ratio of the speed of the host(s) to the average distance between objects in the environment. It is hence possible to mimic the long-term variations in the channel by scaling the speeds of all the nodes down by the same factor as we scale the objects (such as walls) in the environment. For instance, if physical dimensions of the objects are scaled down by a factor of 20, then the speeds of the mobile hosts should also be scaled down by the same factor.
- *Scaling for short-term channel variations:* As noted in Section 3.1, to reproduce the short-term channel variations realistically within the `iWWT`, it is important to be able to produce the short-term variations in channel gain (which, in turn, occur due to variations in phase (ϕ_n's)). Since short-term variations occur for movements of the order of wavelength λ_c, the maximum rate of these variations is governed by the maximum Doppler frequency. Since the host motion will be scaled down to match the long-term variations, there will be a corresponding reduction of the Doppler frequency $f_{\max}$ – this is an undesirable outcome, since the channel in the testbed environment will not behave similar to the real channel. Therefore, we will take steps to realistically reproduce both long-term and short-term channel variations. There are two possible ways to achieving the desired short-term variations, while scaling down mobility:
  - The first method involves inducing artificial variations in the phases ϕ_n through movements of the scatterers in the environment or through the addition of time-varying phase shifts in the surfaces of the scatterers (this would make κ in Equation 1 time-varying). The frequency of these variations needs to be designed in such a way as to cause phase variations corresponding to the desired variations in the real environment. We will pursue this approach in our testbed initially (and later take the approach below, if practical solutions can be developed).
  - Since $f_{\max}$ varies inversely with carrier wavelength λ_c, the second method is simply to scale the carrier wavelength down so as to maintain $f_{\max}$ (in other words, increase carrier frequency f_c). While this is the most direct solution to the problem, it may not be easy to implement. The use of higher carrier frequencies requires either new custom hardware (radios at higher carrier frequency, etc.), or some mechanism to "up-convert" transmissions from off-the-shelf devices to higher frequencies. Up-conversion may be implemented using a "wrapper" around each wireless device. The purpose of the wrapper is to capture transmissions from the wireless device, and to scale up (or "up-convert") the operating frequency, transparent to the wireless device. On the receiving end, the wrapper will perform the appropriate down-conversion. This is indeed a difficult problem, but is facilitated by the linearity of Maxwell's equations [6], and the scaling can potentially be accomplished using standard mixer technologies. When the operating frequency is scaled up, the following changes need to be applied [13]: (1) the linear dimensions of the new antenna need to be $1/n$ times those of the original system where n is the scaling factor; (2) the operating radian frequency ω and the conductivity σ of the materials used in the model needs to be n times that of the original system; and (3) the dielectric permittivity and magnetic permeability used in the model are to be same as in the original system.

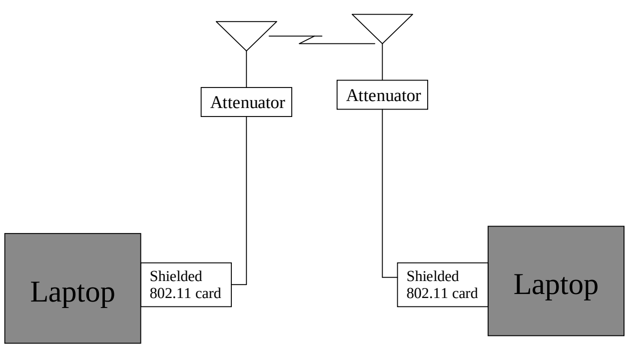
  Since the second method above is quite challenging, our initial testbed will rely on the simpler first method above.

3.2 Scaled Environment

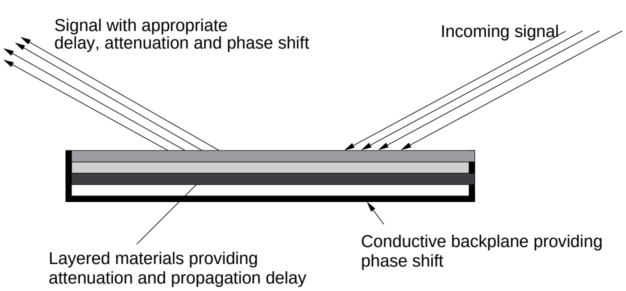
We now outline our plans for design and construction of several building blocks (modules) that will be combined to form a range of propagation effects present in both static and dynamic wireless environments. Additional modules will be developed as the testbed development progresses to provide specialized effects for particular aspects of the research.

Both the modeling and physical construction of these modules and the test environments will begin with simple scenarios and will become more complex through addition of different kinds of modules to arrive at a set of complex propagation environments.

Power Control Module: As discussed earlier, power control is necessary to scale down the wireless network to the small size of the `iWWT` environment. Although many currently available wireless devices provide some power control capability, the degree of flexibility offered by the off-the-shelf devices is not always adequate for our purpose. Therefore, we will incorporate additional mechanisms to achieve power control, while continuing to use off-the-shelf devices. Specifically, we will use wireless cards with external antenna connections, and insert an attenuator between each radio and antenna, as illustrated in Figure 2(a). The internal antennas on the wireless cards will be shielded with a special-purpose copper tape to prevent emission of energy from the internal antennas. Off-the-shelf attenuators will be evaluated first, and if necessary, specialized designs will be developed. Each external power control module will be validated individually in the anechoic chamber. An analogous approach to power control has been taken in a testbed at Sarnoff Corporation as well [5], although the Sarnoff testbed does not have the other desirable features of the `iWWT` testbed (such as controlled mobility, and scaling of other parameters affecting channel characteristics).



(a) Using attenuators and copper tape to implement power control module



(b) Multipath module

Figure 2: Some modules to be used for scaling

Multipath Module: The multipath module will have the capability to introduce time-delay, attenuation, and polarization shifts in a signal on its way from any transmitter to any receiver. A simplified diagram of a multipath module is shown in Figure 2(b). As shown, the modules will be composed of multiple sandwiched layers to achieve appropriate bandwidth characteristics. The module will be composed of layers of absorbing and high permittivity materials mounted to a conducting plate. Absorbing materials will be chosen that do not cause appreciable scattering of the incident signal. The dimensions and properties of the various layers and the signal's angle of incidence from the transmitter will determine how much time delay and attenuation is introduced into the signal, while the conducting plate guarantees the reflective properties. We will design appropriate structures, using analysis and simulations to characterize their properties, as a function of layering, geometry, materials, and dimensions. Initial prototypes may include absorbing material on the ends to dissipate any guided waves in the structure and prevent unintended radiation. Second generation modules will be electronically active, using ferroelectric or piezoelectric materials to induce small-scale (short-term) variations.

Doppler Module: The Doppler effect poses a particular problem in an experimental environment such as this, since it is unrealistic to have objects traveling at high speeds in an enclosed chamber (also, as discussed earlier, speeds need to be scaled down to scale long-term channel behavior). However, since the Doppler shift is equivalent to a *time-varying* phase shift, we will mimic its effect with electronically tunable impedance surfaces [12], which would result in a time-varying change in κ in Equation 1. These surfaces, when equipped with varactor diodes, can change their surface impedance, and hence the reflection phase of an incident signal. One recent work has shown the ability to dynamically tune the phase of a reflected signal in the GHz band, with the rate of phase changes comparable to Doppler frequencies of our interest.

Scattering Module: Scattering takes place in both indoor and outdoor environments when the electromagnetic signal encounters conducting and/or dielectric obstacles in its path. Practically, these obstacles could be people, office furniture, walls, windows, or entire buildings. The kind of scattering that occurs depends on both the size and the properties of the obstacle. To create different kinds of scattering, we will design and validate a number of conducting and dielectric structures that will create scattered signals for the wireless system under test. A related issue is that the humans in a network's environment can also cause scattering if they are using a wireless device or are in close proximity to it. Coarse or detailed "phantom models" can be used to represent humans in the electromagnetic environment [3] – coarse phantom models can be implemented simply using bags of saline solution. This is an example where the testbed sets the stage for investigations that could result in more detailed channel models that take the wireless device *user* into account.

Delays and Delay Spread: One factor that we have not discussed much yet is *propagation delay.* Since speed of light is a difficult parameter to scale in a practical testbed, propagation delays, and, consequently, delay spreads will also be difficult to scale. The delay spread is defined as the difference between the maximum and minimum path delays (τ_n's). The delay spread determines the frequency selectivity of the channel (i.e., variation in channel response as a function of frequency around the carrier frequency f_c). If the delay spread is smaller than inverse of channel bandwidth, then the channel is frequency flat; otherwise, it is frequency selective. Scaling the environment down will scale the delay spread proportionally. If the real environment is frequency flat, then it will remain frequency flat after scaling and the impact of delay spread can be ignored. It is anticipated that the channels of interest in many experiments on the iWWT testbed will be frequency flat. For scenarios where the real environment is frequency selective, if the receivers are not designed to exploit the delay spread for diversity, then again scaling of delay spread is not critical. When the receivers do exploit the delay spreads, additional mechanisms are required to mimic the large delay spread in the scaled environments. For instance, the delay can potentially be increased using dielectric absorbers sandwiched with other materials that will effectively model propagation through longer distances. These modules will encircle the transmitting antenna(s) to emulate one or more units spaced at large distances. The antennas in this case will be specialized designs that take the proximity of the modules into account so that their impedance and radiation characteristics are not adversely affected [1, 2]. Smaller versions of the Doppler modules located close to the transmitting antenna(s) can also be used to introduce delay spread, although these will necessarily introduce an additional shift in phase as well.

3.3 Integration With Emulation

Physical size constraints of the iWWT will impose an upper bound on the size of the network that can be evaluated. The size limit, say, in terms of the number of devices, will depend on the type of devices, however. For instance, the limit on a fixed network of sensors will be much larger than a network of mobile devices. In the past, researchers have investigated integration of live networks with an emulated network – thus, part of the network is real, and part emulated by a (real-time) simulation tool (e.g., [7, 16, 15]). Although we do not plan to develop our own emulation environment, we plan to make it possible to augment the iWWT with emulation environments. In our case, the real network will be inside the iWWT, whereas the devices outside the iWWT would need to be emulated. Towards this goal, we will install wireless devices at the edge of the iWWT which can be controlled by the emulation environment. These devices can then be made to mimic the behavior of the wireless network *outside* the iWWT.

4. SUMMARY

This paper describes a new project at the University of Illinois at Urbana-Champaign to develop a Wireless Wind Tunnel. The Illinois Wireless Wind Tunnel (iWWT) will provide a *scaled* environment for realistic evaluation of wireless networks with static as well as mobile hosts. The iWWT testbed will be used primarily for evaluation of protocols above the physical layer. However, the design of the iWWT requires a careful attention to physical characteristics of the environment. In particular, a scaled wireless environment that mimics realistic short-term and long-term channel variations needs to be developed to implement the iWWT; this paper discusses our preliminary ideas towards achieving this goal.

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