Project Description

1 Introduction

The continuing demand for mobile communications is fueling research into novel communication technologies both at the level of physical devices and networking protocols. At the device level, new technologies such as UWB (Ultra Wide Band), MIMO (Multiple Inputs, Multiple Outputs) and Software Defined Radios (SDR) have the potential to increase physical data rates by an order of magnitude or more. At the networking layers, multi-access networking technologies are being proposed as a way to increase the robustness and reachability of wireless networks. Finally continuing advances in peer-peer, ad-hoc community applications, and on-the-move multimedia applications from the military, homeland security, and bio-terrorism response domains are demanding that the wireless communication technologies deliver high-performance, secure, and scalable communications. Unlike previous revolutions in communication technologies, the next generation of such innovations will rely heavily on cross-layer interactions all the way from the application layer down to the physical devices.

This project proposes to design and develop WHYNET, a wireless hybrid networked testbed. The eventual impact of this research testbed will be to redefine how specific innovations in wireless communication technologies are evaluated in terms of their potential to improve application-level performance as well as how alternative approaches are compared with each other. WHYNET differs from existing testbeds both in its *scope* and *approach*. Its primary objective is to provide researchers at every layer of the protocol stack, from physical devices to transport protocols, a testbed to evaluate the impact of their technology on application level performance, using scalable and realistic operational scenarios. To achieve this objective, WHYNET will use a collection of geographically-distributed physical testbeds integrated with a scalable, multi-tool simulation framework. Such a **hybrid testbed** combines the *realism* of physical testing with the *scalability* of multi-mode simulations and supports a smooth transition from system design to deployment. Protocol prototypes can communicate with simulated low layers for repeatable results, or obtain varying rate real multimedia application traffic for perceptual evaluation. Once the physical hardware devices are ready for testing, a portion of the target network system can be configured with real devices while the rest of the network can still reside in the simulated hardware domain.

When fully deployed, WHYNET will include a physical 3G CDMA testbed, a multiplicity of radio platforms that include narrowband, broadband, and software defined radios, a set of small to medium physical MANET testbeds incorporating novel radio devices, measurement traces and models for a diverse set of antenna and channel conditions, and a large set of reusable protocol models and application scenarios. We will use a representative set of studies to demonstrate the unique contributions of WHYNET for cross-layer optimization schemes in particular and mobile wireless networking in general. These include energy-aware networks, protocols & middleware for multi-access networking, and adaptive transport and security protocols in wireless networks.

2 Related Work

While many campus and community wireless physical networks have been built with low-cost commercial-off-the-shelf (COTS) radio devices, they are seldom useful as general purpose research testbeds because COTS radios do not provide enough flexibility and control to experiment with novel protocol and antenna technologies. We briefly overview both physical and simulation testbeds that have been developed to assist networking research. Among the earliest physical testbeds, Bay Area Research Wireless Access Network (BARWAN) attempted to create a wireless overlay network testbed covering the San Francisco metropolitan area [BSK:95, KBea:96]. High Performance Wireless Research and Education Network (HPWREN) is another testbed aimed to create a purely physical, high performance wireless network in San Diego County. The network includes backbone nodes on the UCSD campus and a number of areas in the county that are generally hard to reach without wireless communications [Ver:01, HYB:02]. Wireless Andrew started as an NSF funded research network at CMU is the largest campus-wide network that supported various wireless networking research activities [BB:97, Hil:99].

Several simulation-oriented networking testbeds have been developed to provide flexible configuration of networks and scenarios: in the public domain, *ns-2* [NS] is a widely used simulation testbed to evaluate networking protocols for Internet sized network systems and GloMoSim [GS] is increasingly used for simulation of wireless, particularly MANET, systems. SSF [SSF, NGJ:99, CLea:99] is a recent parallel simulator being used for analysis of large wired networks. In the commercial world, OPNET [OP] is the most commonly used simulator, with QualNet [QN], the commercial derivative of GloMoSim, finding increasing use in the wireless space. WHYNET will directly incorporate many of the simulation tools that exist and provide open APIs to permit integration of other tools within the framework.

Netbed [NB, WLea:02, RAL:03], which evolved from Emulab, funded by NSF shares the idea with WHYNET of combining simulated, emulated, and physical networks within a single framework. Netbed currently includes approximately 32 nodes geographically distributed across approximately 25 sites, to facilitate networking research activities primarily in the area of conventional wide-area wired networking. NIST Net [NN] implemented as a Linux kernel module emulates the data link layer and below for high layer protocol implementations. Berkeley Emulation Engine (BEE) emulates lower-power digital communication/DSP systems using high-density FPGAs on which Simulink models can be executed to realize fast prototyping of radio implementations [CKea:03, KCea:03]. BEE is an example of a programmable baseband processor for communications applications which lacks the needed RF circuitry to make it into a wireless testbed. However, the scalability of these hybrid techniques [ZN:02a, ZN:02b, DK:02] is limited to the physical size of testbed. Other hybrid techniques that integrate simulated and physical networks have also been proposed for large scale wired network simulation [Dea:95, Nea:97, KMJ:00, Fal:99, SBU:00].

A number of other efforts have helped develop some of the component technologies that will be leveraged by WHYNET to realize a hybrid wireless network testbed.

Under the DARPA Future Combat Systems-Communications (FCS-C) program, a wireless testbed was developed that relied on both physical measurements and simulations to evaluate performance of protocols and devices using directional antennas. For this study, a group of vehicles, enhanced with communication assets being tested, followed a scripted course at a site that included buildings, some terrain and foliage effects. The position of the vehicles was recorded continuously via vehicle-mounted GPS systems, and the message traffic was generated using the MGEN/DREC software developed by NRL [MGEN, BH:03]. A trace of the packets received by each vehicle was also recorded and summary performance characteristics were computed from the packet trace. Detailed simulation models of the communication technology and channel characteristics were developed, and identical MGEN/DREC code was used to generate traffic in the model. The mobility traces collected during the field exercise were used to define the mobility of the simulated entities and the results predicted by the model were validated against field measurements. The models were then extended to predict system performance in various scaled scenarios. The *methodology* and many of the *tools* developed as part of this study, including MGEN/DREC, the channel characterization methodology, and the models will be directly leveraged by WHYNET.

The DARPA Network Modeling and Simulation (NMS) program has produced a number of modeling & simulation technologies with the objective of real time analysis and control of networks [NMS]. These efforts include the Georgia Tech RTI/Backplane [Fuj:98, RAea:01] which federates multiple packet level simulators and allows them to freely exchange IP packets by offering a packet contents translation service, a parallel and distributed version of *ns-2* [RFA:99], the SSF scalable simulator for wired networks, JavaSim [JS], a Java-based simulator for wireless networks, and the Maya framework [Zea:03] which efficiently integrates analytical and discrete-event models and also manages time synchronization with physical networks. Many of these techniques and tools will be directly leveraged within WHYNET.

3 Key Research Components and Objectives

3.1 WHYNET framework (Bagrodia, Fitz, Rao, Srivastava, Shen, Takai)

WHYNET is a highly scalable network testbed that can support the design and development of wireless devices and protocols by seamlessly incorporating real applications and protocol implementations with simulation models. A wireless testbed with physical radio devices can provide invaluable insights to real-world issues and performance of the hardware devices, but it may be hard, or at least very resource intensive to obtain repeatable results from such a testbed. This is primarily due to the nature of the *unguided wireless media* and its close coupling to the surrounding environments (i.e., weather and movements of surrounding obstacles), which can exhibit widely varying and time-dependent results. The magnitude of this problem increases as the target network system becomes larger and more heterogeneous. On the other hand, simulation tools can provide great flexibility in evaluating alternative technologies. Simulation models can provide repeatable conditions, create critical but hard to realize scenarios (i.e., overloading, emergency etc.), and configure the system with yet expensive hardware components or technologies in an economical manner. However, unrealistic assumptions or abstractions in the protocol or device models or in the evaluation scenarios may produce misleading or erroneous results whose impact is known only when the system is deployed.

WHYNET aims to combine the strengths of the preceding approaches by accommodating both physical and virtual components to configure a network. Virtual components can be measurements (e.g., radio resource measurements, packet timing) or simulation models (e.g., device models in MATLAB and/or Simulink, protocol models in *ns-2*, GloMoSim or QualNet); physical components include physical radio devices and implementations of protocols and applications. These components are mixed and combined effectively to study the viability of novel networking technologies to provide wide-area heterogeneous communications. The two pictures below illustrate overall WHYNET framework architecture; the left depicts the integration of real and virtual network components in the protocol stack, and the right shows how multiple heterogeneous physical testbeds located at different locations will be integrated via simulation network testbeds.

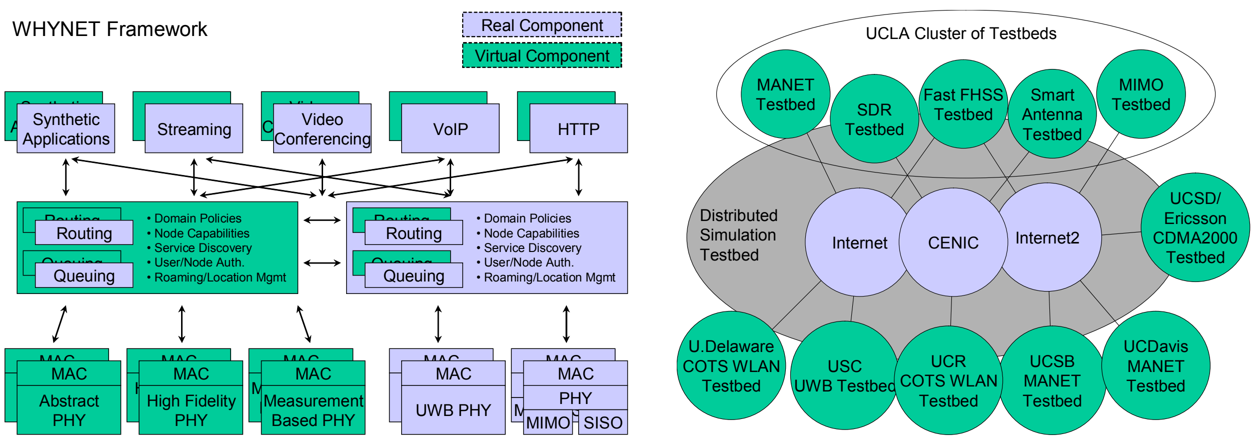

Figure 1: WHYNET architecture (left: protocol stack, right: geographically distributed testbeds).

The primary challenges in developing WHYNET components involve the design and implementation of the following interfaces:

- Integration of simulated and physical components at multiple layers of the protocol stack
- Integration of simulators that use dramatically different time granularities
- Integration of geographically distributed physical testbeds with simulated sub-networks

In the remainder of this section, we provide a brief description of our approach towards the design and implementation of each of these interfaces.

3.1.1 Integration of simulated and physical components

WHYNET will define a generic set of APIs based on the protocol stack of physical network systems. This allows operational protocol implementations and applications to be directly executed within the WHYNET framework. It also allows these physical components to transparently communicate with simulated components without any modifications. These APIs will be derived directly from the GloMoSim [GS, LTea:00] and QualNet [QN] interfaces, where their ability to support the preceding capabilities have already been demonstrated [XTea:01, Zea:03]. Under the Maya project at UCLA, a number of time management mechanisms have been implemented to synchronize simulated components with real time, and to transparently replace those simulated components with protocol implementations and physical devices [Zea:03]. These techniques will be directly incorporated into WHYNET and expanded to provide synchronization for a geographically-distributed testbed.

WHYNET will use the packet translation service developed at Georgia Tech [RFA:99, RAea:01], to integrate multiple simulators such as ns-2, GloMoSim, OPNET and QualNet whose internal representations of packets are significantly different from each other. The viability of this approach to provide seamless exchange of packets has already been demonstrated for a federation that includes parallel ns-2, GloMoSim, and QualNet. The packet translation service will be expanded to use the WHYNET APIs and thus to allow integration of models at different layers of the protocol stack, possibly modeled using multiple simulators.

Multimedia applications including video conferencing and VoIP generate content-dependent, variable rate traffic that requires different types and levels of QoS in the network. Such applications can adapt to changes in network conditions such as end-to-end communication latency, throughput and jitters by modifying their own behavior (e.g., changing the traffic rate). Such adaptive behavior may be hard to model in simulations, and even traces from the real applications cannot accurately reproduce their adaptive aspect. The WHYNET framework allows real multimedia applications to be directly linked to the simulated protocol stack. This provides protocol designers an accurate traffic scenario as well as enables a *perceptual evaluation* within the simulated context. For instance, a protocol designer can examine parameter ranges of the target protocol for a video conferencing application by perceptually evaluating the voice and image qualities of application clients.

Beyond providing a more accurate evaluation framework, the hybrid simulator will facilitate a smooth transition from an abstract simulation model to an operational implementation within a single framework. For instance, a MAC protocol designer can use abstract physical layer models in *ns-2* to examine alternative algorithms within WHYNET at an early stage of protocol design. Once a prototype of the protocol is developed, it can be incorporated and evaluated with a measurement based radio device model that gives more realistic, but well-controlled sequences of events. The measurement based radio device can be further replaced by a high-fidelity adaptive radio device model written in Simulink in order to evaluate cross layer interactions between the physical layer and the MAC sub-layer. Finally, real radio devices that include the designed MAC protocol implementation can be tested in a physical network without having to change the higher layers within WHYNET.

3.1.2 Integration of simulators with dramatically different time granularities

Accurate modeling of a wireless link involves many issues at the data link and physical layers. Although packet level modeling is often sufficient, substantial insights may be drawn from integration of more detailed device level models into a network simulator [Gea:03]. A primary challenge of such integration is the reconciliation among the widely varying time granularities at which packet- and device-level simulators operate. For instance, an RF radio device model targeted at 5GHz in a time stepped simulator like Simulink may need inputs from the underlying channel model every tenth of a nanosecond, while a radio baseband model in the same simulator may only require an input every 10 nanoseconds. A MAC protocol modeled in a discrete-event simulator may use a time scale in the order of microseconds, whereas an application model running on top of the protocol stack may only generate an event every 10 seconds. We have successfully integrated an OFDM radio and channel model into a QualNet protocol model by developing appropriate interfaces to facilitate the integration and then by designing dynamic time management techniques to reduce the computational burden [Gea:03]. The WHYNET framework will effectively utilize parallel and distributed computing resources and minimize computing resource utilization inefficiencies to execute models that require dramatically different time granularities. We will expand the dynamic time management schemes to support efficient simulation of multiple sub-network models whose levels of fidelity can be substantially different from each other.

3.1.3 Integration of geographically distributed physical testbeds with simulated sub-networks

WHYNET will integrate multiple wireless physical testbeds geographically distributed primarily over the Southern California area via simulated wireless sub-networks. Those physical testbeds include Cal-$(IT)^2$ CDMA 2000 Network Testbed located at UCSD and San Diego facilities of Ericsson, and wireless MANET testbeds with both COTS and new radios at five UC campuses (Los Angeles, San Diego, Riverside, Santa Barbara and Davis) as well as USC and University of Delaware campuses. In particular, the two CDMA 2000 cells located at UCSD provides WHYNET with a non-IP protocol stack to which networking researchers can hardly have access. Further, several wireless network testbeds with novel radio technologies at UCLA and USC give protocol designers early access to radios that will be on the commercial market in the next 5 years. These Southern California testbed locations are interconnected via a 10 Gb/s CENIC High Performance Research network that provide low latency interconnection infrastructures crucial for WHYNET to perform geographically distributed real-time simulation.

The geographically-distributed physical testbeds will be integrated with a highly scalable simulation framework. Previous work has already demonstrated the feasibility of integrating local physical and simulated components [NN, XTea:01, Zea:03], and integration of geographically-distributed simulators [WLea:02, RAL:03]. We will extend these efforts to develop *a hybrid framework that can synchronize with the geographically distributed physical testbeds* using specific gateways. The primary issue in such systems is to have simulations that are capable of running faster than real-time and to minimize communication latency between the simulated and physical testbeds. Preceding research on parallel execution of GloMoSim, QualNet, and ns-2 [GS, QN, NS] funded under NSF and DARPA programs will be substantially leveraged to provide the needed simulation capabilities. WHYNET will use the CENIC research network to provide the low-latency connectivity to the remote sites and use a network of 4-way symmetric multiprocessors to run parallel simulations that meet the required constraints.

The integration of this diverse set of wireless networks with incompatible protocol stacks with significantly different networking capabilities will showcase the WHYNET framework as one wide-area heterogeneous wireless network testbed that can accommodate region-wide interworking studies. For instance, quality of a voice session originated from a cell phone to a PDA in a UWB PAN can be perceptually evaluated through CDMA2000 1xRTT base station, IP backbone, (simulated) campus-wide MANET and UWB PAN with H.323, VoIP and other high layer protocols that WHYNET can offer.

3.2 Repository of networking scenarios, measurements, models, and implementations (All)

A major component of this effort is to produce a repository of measurements, traces and models for channel, radio, protocol & application traffic.

While channel impulse responses under various environments can be measured, they cannot recreate certain environmental aspects such as channel correlations of nearby mobiles for a given transmission, which can only be collected via network-wide experiments. Further, channel measurements alone are not enough to reproduce networking experiments, as there are many other scenario parameters including mobility, traffic sources and destinations, and route tables of mobiles. WHYNET will be an ideal vehicle for collecting wireless networking measurements that can be used for performance analysis studies using the testbed as well as network simulations.

We will extend existing traffic generation and logging tools like MGEN/DREC [MGEN] to collect additional information during networking exercises, including hop-by-hop timing data for both control and data packets, RSSI (Received Signal Strength Indication), noise floor and frame error rates for a given SNR. This data will subsequently be post-processed and extrapolated to generate realistic but repeatable networking scenarios with wide applicability. Extrapolation of measurements is performed with representative propagation and channel models together with a real-time channel emulator in order to measure and calibrate frame error rates of given radio devices crucial to create reliable measurement based radio models with consistent performance. The measurement data will be useful for establishing the base performance of high layer protocols and radio devices, analysis of cross-layer interactions, as well as fair comparisons of protocols system alternatives.

The enhanced logging capability will be embedded within WHYNET such that network usage, including access logs, traffic loads, and types of applications, are constantly monitored within the physical testbed. Such measured data sets, while commonly available for wired networks [BC:03, BNC:03], are relatively scarce for wireless networks and will be an invaluable source of realistic traffic traces. This data will serve yet another purpose -- validation of simulation models. As shown in [TMea:01], models of even widely used protocols like 802.11b, in different simulators, can predict widely varying effects for a given scenario, and it is hard to identify the 'correct' model. Model validations against measurements, while invaluable, are resource-intensive and ready availability of measured data from the WHYNET logging facility will remove a major impediment. As WHYNET includes next generation physical layer technologies, it will be possible to validate contemporary cards like IEEE 802.11a/b as well as directional antenna [TMea:02], and power consumption models for sensors and actuators in ns-2 [PSS:00, PSS:01, SPS:01].

In addition to measurements and traces from the physical testbed, WHYNET will also generate a rich set of wireless protocol models using simulators that are in common use within the networking research community. A rich set of wireless system models already exist in Ns-2, GloMoSim, and QualNet, and we expect the model library to be enhanced with a richer set of models, particularly for multi-access networking, power aware networking, adaptive transport protocols, network security, and QoS.

3.3 Novel Radio technologies in WHYNET (Fitz, Daneshrad, Mitra)

Wireless networks are distinguished by the close coupling between the radio channel characteristics and higher layer protocols. Emerging radio technologies such as Ultra Wide Band (UWB), Multi-Input Multi-Output (MIMO) and Software Defined Radio (SDR) will significantly impact the overall network performance, robustness, flexibility, and cross-layer interactions. However, to realize their full potential these technologies need support from higher layer protocols, particularly from media access and routing protocols. Existing higher layer protocols are currently unable to exploit the unique features of these technologies and thus cannot achieve maximal utility. For example, SDR with its ability to dynamically alter the physical waveform being utilized by the radio will require high-layer protocols that support physical layer reconfiguration. The testbed will incorporate a rich palette of accurate simulation models as well as instrumented lab-scale and deployment-scale test beds that can be incorporated in a hybrid simulation. Physical traces, experimental measurements, and simulation models will be collected in a host of networking scenarios and included in the repository. This will permit the developers of higher layer protocols to study the coupling with emerging radio technologies, and also permit the developers of new radio technologies to study their performance in the overall system and application context.

The WHYNET wireless testbed will consist of a multiplicity of radio platforms which will be made available to the greater research community. These include:

- Narrowband (fc=220 MHz, BW=4kHz) real-time software defined radios
- Narrowband (fc=928MHz, BW=80kHz) Fast FHSS testbed
- Broadband (fc=2.4 GHz, BW=15 MHz) Real-time Software defined radios
- Mediumband (fc=2.4 GHz, BW=5MHz) real-time equalized QAM radios with smart antennas
- Broadband (fc=5.2 GHz, BW=25MHz) ASIC+Firmware based MIMO radios
- Ultra Wideband Radios

All of these radios are currently under development and are being funded through a number of sponsors including ONR, NSF, ARO, DARPA, and industrial sponsors. The integration of the individual radios as well as clusters of up to 15 radios of the same or different capability, into the WHYNET framework will provide a hitherto unavailable capability for wireless system designers that can help fuel multidisciplinary wireless network research and education for years to come.

Each radio will provide users (researchers or classroom students) with full access to all PHY layer parameters, such that the higher layers can easily dictate radio parameters that include bandwidth, transmit power, packet structure, FEC coding/decoding, and smart antenna processing, to name a few. Moreover, the higher layers can poll the radio for information such as Received SNR/SINR and BER, estimates of the channel impulse response, state of synchronization loops, FER, to determine appropriate operations.

WHYNET will not only integrate all 6 radio platforms into the physical prototype, but also capture the operation of the radios in a set of simulation models. Both the simulation models and measured testbed results will be catalogued and filed within the repository of networking scenarios created under this project. This is an invaluable resource to future networking and radio researchers and educators.

3.3.1 Narrowband SDR Testbed

The testbed uses the Narrowband Radio services band (220-222MHz) setup by the FCC for bandwidth efficient communication. Communication is envisioned with 5kHz channel spacing and 4kHz of useful spectrum. Since 220MHz has good propagation characteristics, this radio will provide wide area coverage. Our testbed achieves high bandwidth efficiency and good performance by applying the state of the art in communication theory. Transmitted power of up to 100Watts is possible and supported ranges greater than 10 miles have been demonstrated in field tests. The testbed consists of a wide variety of components that can be interchanged to achieve a desired network architecture (a single antenna node is shown in Figure 2). This SDR testbed has been used in infrastructure (base station

Figure 2: Mobile unit in SDR Testbed

based) systems covering an entire metropolitan area and in MANET architectures in campus wide deployments.

The testbed implements all algorithms in software. The physical layer, and network layer functionality is implemented in software. This allows the systems to be modified when new and better ways of processing the signals become available. Papers documenting the progress on this testbed are [BF:01, EF:98, Fea:96, Fvt:97, Fea:97, Fea:03, FTM:01, Gea:97, Lea:01, Wea:01,Wea:03, Xea:03, Zea:01].

One of the goals in this research project is to set up a realistic wireless testbed using the components of this SDR testbed and interface this testbed with WHYNET. We propose procuring multiple nodes for the testbed to set up realistic MANET scenarios and infrastructure based scenarios. This lab-scale and deployment-scale test bed will be incorporated in a hybrid simulation. This will permit the developers of higher layer protocols to study the coupling with emerging radio technologies (e.g., MIMO), and also permit the developers of new radio technologies to study their performance in the overall system and application context.

3.3.2 Mediumband real-time equalized QAM radios with smart antenna processing

The 5 Mbaud QAM testbed was the first of a series of testbeds developed at UCLA to help validate theoretical and simulation results with experimental observations. The testbed was, and continues to be, the only experimental platform with real time adaptive equalization and real time smart antenna processing. Initial measurements using the testbed were first reported in [Kim:99]. Follow on work compared simulation and experimental results when combined diversity and adaptive equalization are employed [Frig:00, Frig:02].

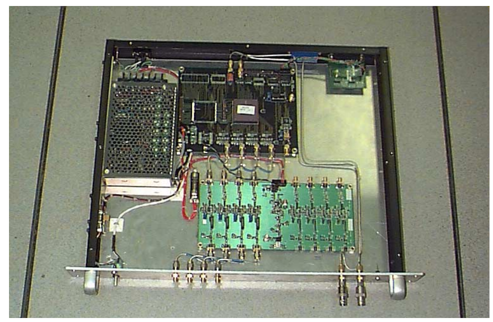

Figure 3: Baseband section of QAM testbed. Real time Adaptive equalization and Smart antenna processing are realized in DIVERQAM ASIC developed at UCLA

Figure 3 shows a functional block diagram of the receiver, as well as a picture of the baseband section of the testbed which is centered around the UCLA developed DIVERQAM ASIC [Put:99]. The availability of an operational testbed on day one will help maximize the overall impact of WHYNET. Given that the physical hardware is available and has been fully characterized by past work. What remains is to simply incorporate the simulation, models, the actual hardware, and the networking scenarios with the network testbed and make it available to the scientific community at large.

3.3.3 Narrowband Software Defined Fast FHSS Testbed

Traditional frequency hopped spread spectrum radios suffer from their inability to quickly hop from one carrier frequency to the next. In fact hopping rates are limited to a maximum of 10 khops/sec at best. The FHSS testbed developed at UCLA and initially reported in [Cab:01, Zou:01]. The unique architectural innovation in this testbed is the use of a direct digital frequency synthesizer (DDFS) that allows the signal to hop anywhere within the 902 MHz to 928 MHz ISM band at 80 Khops/sec. The baseband section of this testbed is centered around a powerful TI C6x processor that supports all the baseband PHY layer functionality as well as all MAC, and network related functions that need to interact with, and to operate in close proximity with the radio. The exceptionally high hopping rates delivered by this radio provide unique waveforms that have not been possible before.

3.3.4 Wideband ASIC+FPGA based MIMO radios.

Multi-Input-Multi-Output (MIMO) systems in wireless communications have received considerable attention in the past few years. Communication theorist have shown that under certain channel and environmental conditions, MIMO system theory can be applied to substantially increase the spectral efficiency of wireless communication systems by orders of magnitude (specially at low outage levels). To date, the experimental platforms that have been reported for MIMO communications have been limited in bandwidth to 100's of KHz, and often do not provide real-time data processing.

The MIMO testbed activity at UCLA will culminate in a real-time MIMO system capable of processing 25 MHz of signal bandwidth with MIMO configurations as large as 4x4. Real time processing of the transmitted data is an important factor in the study of interactions of higher layer protocols in the presence of dynamic real-time interference conditions that arise at the cluster and network levels. To make real-time operations possible, the research will develop state of the art VLSI ASICs that deliver 100’s of Giga Operations Per Second (GOPS) of processing power. The work is currently in its second year of activity and has produced a fully functional RF front end operating at 5.2 GHz and a functional MIMO modulator ASIC.

As part of this proposal we will embed the powerful ASICs on a board with a large number of high speed FPGAs. This approach results in a programmable fabric that can be used to implement high speed MAC, other data-link layer and network layer protocols that are not hampered by the sluggishness of software programmable devices. The result is a powerful and flexible platform that can support many forms of MIMO based wireless data communications.

3.3.5 Wideband Software Defined Radio

The wideband SDR testbed activity is ongoing. The system is very powerful and has been specified to support realistic wideband wireless communications (Fig. 5 in Facilities shows the testing of an 802.11g implementation). Four channels are supported in both the transmitter and the receiver processor. The system supports up to 15MHz of RF bandwidth on each channel utilizing an industry standard VME bus and Raceway interconnect systems. It is designed to have high computation power in a parallel structure with convenient and fast inter-processor communications, high I/O bandwidth, and easy upgrading and extending capabilities. The system consists of up and down converter cards, an FPGA board, multiple processor boards and a large memory for data capture

One of the goals in this research project is to use this SDR testbed to facilitate further physical layer testbed development. While realistic wideband real-time testbed implementations will have to rely on FPGA and custom IC development to achieve widespread deployment, the wideband SDR radio platform at UCLA is a valuable tool during the engineering design phases of such developments. This SDR radio testbed will allow student researchers to have access to channel conditions and characteristics while developing the implementations and algorithms for high performance wireless modems.

This flexibility improves the design process and the final radio testbed. Likewise this project will give the developers of new radio technologies a SDR platform with an interface to the WHYNET simulation paradigm. This interface will allow physical layer researchers to have immediate feedback about the efficacy of algorithms in realistic network deployments.

3.3.6 Ultra Wideband Radio

Ultra-wideband communication systems are those where the 3dB transmission bandwidth is at least 25% of the center frequency of radiation. For this project, we would use the resources of USC’s Ultra Laboratory (http://ultra.usc.edu), which is dedicated to experimental research in UWB communications, signal processing, and propagation. The unique feature of the laboratory is the ability to conduct truly UWB experiments. Recent experiments include: indoor propagation measurements and antenna measurements. The capability for outdoor propagation measurements also exists and this capability will be exploited for the current proposal.

Due to the fact that UWB research is still in its infancy, designing a fully functioning testbed poses some challenges – off the shelf components are not readily available for building SDR-based UWB radios. However, it is precisely this feature that drives the proposed work. Thus, we shall approach the UWB aspect of WHYNET from multiple perspectives simultaneously. We proposed to develop: a simulation environment for the UWB channel by exploiting measurement data from the Ultra Lab; the integration of prototype commercial UWB radios (from Xtreme Spectrum) into the testbed; the development of abstract channel models for use in receiver algorithm design and the modeling of the performance of these novel receiver algorithms. The results of these simultaneous efforts will necessarily influence each other and suggest design changes for the testbed. We also propose to consider designs which meet complexity constraints imposed by the hardware while optimizing performance. We note that the current system in the UltraLab does not “communicate” data, but rather is analyzing the transmission and reception of individual pulses. Thus, we propose to advance the capability of the system through the design of basic synchronization and acquisition algorithms.

Much of UWB research thus far has focused on physical layer and radio hardware design issues without consideration of their interaction with the upper layers of the system. To facilitate development of higher layer protocols optimized for UWB, as well as to study critical cross-layer interactions, we propose to develop abstract statistical models that capture the aggregate behavior of the lower layers of the UWB systems, and include these models in the repository of networking scenarios.

3.3.7 Cluster of Heterogeneous Nodes

The geographical proximity of the available radio testbeds (five at UCLA and one at USC) enables us to create clusters of heterogeneous nodes consisting of narrowband radios, MIMO radios, UWB radios, etc. When integrated into the WHYNET framework, this enables the research community at large to experiment with, and design protocols with full knowledge of the unique real-time interference patterns and dynamics of such a heterogeneous clusters.

3.4 Networking Research Studies Using WHYNET

WHYNET offers unique features which set it apart from most existing single investigator or single site testbeds, namely: multiple users, multiple sites, rich set of modular building blocks (at all protocol layers), hybrid simulation platform, calibrated and well instrumented benchmarks, multiple applications. WHYNET is ideally suited for research, design and testing of next generation, scalable wireless protocols.

The following studies demonstrate the utility of WHYNET for design, development and deployment of wireless mobile network systems, which are hard to configure without capabilities that WHYNET can provide.

3.4.1 Sensor Networks (Rao, Srivastava, Tripathi, Shen)

Networks of wireless devices with sensing and actuation abilities to monitor and manipulate the environment have emerged as a new class of ad hoc wireless networks that are quite distinct from conventional wireless where much of the traditional wireless networking research has focused. Physical coupling, large scale, severe energy constraint, harsh propagation terrain, coupling between radio and sensing aspects, controlled mobility, and focus on distributed computation as opposed to bit transport are some of the attributes that distinguish these networks from conventional cellular and mobile ad hoc wireless networks.

The proposed research activity will focus on two aspects. First, we will directly contribute to the WHYNET infrastructure in the form of simulation models and lab-scale physical test beds. Our previous research has led to specialized simulation tools and models for the three distinctive aspects of sensor networks: communication, computation, and sensing. A representative example of the new class of simulation tools and models is SensorSim [PSS:00, PSS:01, SPS:01] which incorporates models of sensor channels, targets, sensor nodes, batteries etc. We envision contributing SensorSim-like capabilities to the testbed infrastructure. Moreover, we will add the ability to model a fourth distinctive aspect of sensor networks: actuation. Models incorporating energy and performance aspects for directional antennas that can be mechanically rotated and sensor nodes that may be mechanically moved will be created. Besides simulation models, we will also link to WHYNET sensor network test beds that have resulted from prior research such as the Smart Kindergarten system (NSF ITR) [SMP:01], the sensor networks systems at Center for Embedded Networked Sensing (CENS: NSF STC), and the ONR-funded AINS test bed consisting of a variety of ground-based static, ground-based mobile, and air-borne sensor nodes.

The second element of our proposed activity will be new research that is directly enabled by the existence of the WHYNET test bed. One research focus will be on the management of sensor data from geographically distributed sensor networks. The ability to fuse data from geographically disparate sensor networks is crucial to many applications such as disaster relief. Another research focus will on the interaction between static sensor nodes and nodes with controlled or uncontrolled mobility (robots, humans) belonging to a MANET or a communication backbone. This interaction between static and mobile nodes is crucial to the extraction of information from sensor networks and using it to guide decision-making. WHYNET's ability to combine disparate and distributed wireless network elements will be a crucial enabler for both these research areas.

3.4.2 Power-aware Networking (Srivastava, Rao, Daneshrad)

Battery energy limitations are a significant showstopper for wireless networks. Indeed, energy has become a primary metric when designing radios, protocol stacks, node architectures, and applications for wireless networking. However, traditional research has not addressed energy issues adequately. Influenced by traditional communication theory, usually wireless protocol designers have made assumptions such as transmit power consumption >> receive power consumption, idle power is negligible, transmit power is dominated by the RF power consumption etc. Unfortunately the reality is quite different. For example, recent research [SRS:03, RGSS:03] has shown that radio electronics is a key determinant of the power consumption, particularly for short-range radios (10s of meters). Once such effects are considered, one realizes that for short-range radios, receive and idle power are comparable if not more than transmit power. Ignoring them leads to wrong protocol design.

Our activity in this area will be two-fold. First, we will create detailed energy models of radios based on first principles to better capture electronic effects and the variation of energy as a function of the radio operation mode. In particular, we will seek to capture electronics related effects such as radio start time, variation of energy with modulation rate, variation of energy with transmit power etc. Closely related will be models of batteries themselves since non-linear battery effects such as dependence on rate of consumption and relaxation effects impact the battery life, and are directly influenced by the protocols.

Second, we will create an integrated power-aware network protocol stack that embodies intra and cross-layer techniques for improving energy awareness and energy efficiency. The primary metric of interest will be the amount and location of energy spent per good application level bit transported end-to-end. From our existing research we will leverage techniques for distributed radio shutdown [STGS:02] and power-aware wireless packet scheduling [RGSS:03] to create a framework to exploit energy-performance scaling control knobs provided by the radios and the protocols. New avenues of investigation will include power-aware transport protocols that trade-off energy against accuracy and reliability, and network-wide control knobs for energy–performance scaling. The resulting protocol stack will be evaluated in the context of a variety of wireless nodes, via a mix of simulation, emulation, and implementation on WHYNET.

3.4.3 Directional communications in MANETs (Takai, Krishnamurthy, Tripathi, Daneshrad)

While the antenna hardware itself will soon be ready for the deployment at mobile stations, existing higher layer protocols may not be able to fully exploit the potentials of directional antennas. In particular, recent studies on the use of directional antennas in mobile ad hoc networks, or MANETs [BHea:01, BG:02, CYea:02, KSV:00, NYea:00, Ram:01, SGZ:01, San:02, TMea:02], have shown significant increase in network capacity. New generation of smart antennas (SA) are expected to provide much better spatial reuse and effective extension of communication range.

One important aspect of communication range extension using directional antennas is possible increase of interference due to high EIRP (Effective Isotropic Radiated Power) in the transmission direction. High interference could increase contention among network nodes attempting to acquire the channel access, resulting in severely reduced network capacity. This is fatal for dense networks where many links share the same space for their data communications. Therefore, communication range extension should be based on the network density and be used primarily for sparse networks with partitions. However, identifying the effective network density for communication range extension is also challenging in MANETs due to node mobility and routing protocol behavior. Network nodes not participating in routing any traffic should not be counted when computing the effective network density. This results in instantaneous density changes even for networks without mobility.

Using WHYNET, a system stack to achieve adaptive range extension using directional antennas can effectively be designed and evaluated. For instance, a routing protocol modeled in ns-2 or QualNet that performs session handoff based on link quality can be tested and tuned with real VoIP sessions for perceptual evaluation. A link quality assessment mechanism in a MAC protocol can be designed with measurements of channel conditions and correlated frame error rates, which can then be evaluated in real time with physical radio devices in real-world environments. Before fabrication, an adaptive beamforming algorithm modeled in MATLAB can be evaluated with higher layer protocol prototypes, physical radio devices and an RF channel emulator that creates repeatable but realistic channel conditions. These are several representative cases where each system component is designed in virtual (simulation) domain, and then evaluated with realistic networking contexts in physical domain. Transparent interactions of real and virtual system components in WHYNET allow smooth transition of system design to a deployable physical network system even if the target system is highly adaptive and involves high degrees of cross layer interactions.

3.4.4 ABC (Always Best Connected): integration of wireless domains (Rao, Gerla, Mohapatra)

WHYNET will offer multiple options for wireless connectivity, including very high rate but short range UWB and Bluetooth PAN radios, longer range IEEE 802.11a/b/g WLAN radios and even longer range but lower rate CDMA services. **ABC (Always Best Connected)** service based on a multi-access networking concept will enable a user to seamlessly switch his/her wireless devices between different wireless access networks. Detection, selection and authentication of the “best” wireless access will be three major functionalities to be offered by the ABC service. One example of ABC applications will be a sensor network with a mix of battery driven low power sensor nodes and network gateway nodes with line power. The low power nodes send audio/video clips through the ad-hoc network to an external network via a selected gateway node. ABC will dynamically find the best access network, best gateway node and best path to gateway based on remaining battery power. ABC will be key also in the interconnection of ad hoc networks.

Many ad hoc network applications (search and rescue, group collaboration, etc) call for the interconnection of remote, instantly (re)configured ad hoc network islands using an existing infrastructure. For example, multiple rescue teams fighting a forest fire may interconnect via LEO satellites; or student study groups form small ad hoc networks interconnected with GPRS or CDMA. These **"federations" of ad hoc islands** pose a brand new host of issues in service discovery, authentication, security, QoS, and transport protocols. They also pose the problem of protocol compatibility across islands. WHYNET offers the opportunity to create and extensively test ad hoc federations across different campuses. The ABC strategy will support peer-to-peer connectivity between ad-hoc networks by recommending the best interconnect strategy based on available access. The application could be members of a search and rescue team, a multiplayer game or a sensor network. When an ad hoc team moves outside WLAN coverage, ABC will select the node to connect to the rest of the p2p overlay via CDMA2000. Other federated testbed and ABC research issues include: multi-island routing in a highly mobile environment (candidate solutions may be Mobile IP overlays and Landmark routing [PGX:00]); security (user authentication and user data protection is the ad hoc P2P environment based on an open key infrastructure must be investigated); performance and QoS (the opportunity to use the multiple interfaces offered by ABC should be utilized to give both better capacity by means of flow aggregation and better connectivity robustness) , and; configuration and service discovery. In Service Discovery, it is no longer possible to maintain static bindings between clients and servers. We will recast the client-server model into a peer-to-peer model; nodes can offer services and resources to any of their peers, as well as discover new services for their own needs. An important design issues will include caching and path maintenance for the server nodes.

3.4.5 Adaptive, cross-layer protocol design: QoS support and reliable transport (Gerla, Mahapatra, Shen, Tripathi, Krishnamurthy, Molle)

New technologies including UWB and MIMO can increase the physical data rate by an order of magnitude. However, higher layers must be "aware" of the technology to effectively exploit them. This multi-layer adaptation must account for layer details currently not supported by conventional simulation tools or testbeds. The hybrid platform of WHYNET will critical to enable the entire processes of design and development of the tightly integrated wireless protocols. Most critically dependent on adaptation is QoS support, as it encompasses issues at all layers [MLG:03]. For example end to end QoS depends not only on channel modulation but also on its interplay with source compression in the application. At the MAC layer, a fully distributed scheme is needed that should solve the hidden and exposed terminal problems while providing support for real-time traffic. Techniques like MACA [Kar:90], MACAW [BDea:94], and IEEE 802.11 DCF are not adequate for QoS provisioning. New QoS-aware MAC schemes must be explored and evaluated with the assistance of powerful simulation tools. In the network layer, the QoS-aware path determination must be integrated with route discovery [LM:02]. Reliable, congestion controlled, QoS aware ad hoc multicast must effectively bridge MAC and application layer functions [TOea:02]. The transport layer must distinguish packet losses due to wireless channel noise and route changes. Conventional TCP interprets packet loss as congestion, leading to poor throughput. Moreover, previous studies suggest that the interaction of TCP and IEEE 802.11 MAC leads to further degradation and even capture. To improve TCP performance we will explore multiple paths, concurrent multiple access points and enhanced MAC and physical layer technologies. We plan to investigate adaptive transport protocols that provide concurrent and prioritized streaming capabilities and can adapt to different networking conditions. In essence, we will consider strategies that: (a) split the data over multiple streams; (b) send different (or the same) streams over different physical paths for reliability and/or bandwidth aggregation. Note that multi-streaming and multi-homing are the two of the key features of the emerging IETF Stream Control Transmission Protocol (SCTP). We propose to use the SCTP multi-homing feature to interoperate with multi-path routing protocols so that multiple streams may be transmitted concurrently over multiple routes. At the application-level, QoS adaptive strategies will include adaptive compression algorithms, joint source-channel coding and joint source-network coding schemes. QoS provisioning using overlays [GM:03b] can also be explored in the federated environment, with network-level QoS support in each island and application-layer QoS across islands.

3.4.6 Scalable Security (Royer, Mohapatra, Gerla)

Wireless networks are particularly vulnerable due to the broadcast nature of the communication channel, the portability of the nodes, and the reliance on other network nodes for data packet forwarding. Current wireless networks security techniques incorporate a wide range of approaches, from secure routing protocols [SDea:02, HPJ:02, PH:02], to key distribution strategies, intrusion detection, and monitoring systems [ZL:00]. WHYNET will provide a large-scale wireless network in which the security techniques can be deployed and attacks can be injected. We intend to investigate the performance of a wide range of security techniques, including authentication schemes, secure routing protocols, and access control. For instance, two aspects of authentication, node identity authentication in spite of intrusions, and data origin authentication in broadcast channels, are critical problems in mobile wireless networks. The proposed countermeasures, such as TESLA [PCea:01], trade off latency for security service. The effectiveness of such protocols, especially for real time applications, can only be accurately verified in a real world testbed that recreates a realistic traffic environment.

In addition to the abovementioned security techniques, intrusions and malicious nodes can be modeled within the testbed, and the utility of both existing and future security protocols can be determined. One of the hindrances to current intrusion detection work in ad hoc networks is the lack of knowledge of typical user behavior in a wireless network. To enable anomaly-based intrusion detection, usage models must be developed so that anomalies can be characterized. Monitoring techniques deployed within the testbed will enable the creation of data repositories representing typical user behavior so that anomalous behavior can be determined. Because the testbed consists of a diverse set of users over multiple campuses, a large number of user behaviors can be recorded and the recorded behavior used to generate models. Once the user behavior is modeled, anomaly based intrusion detection can be deployed.. In addition, because the testbed is distributed across multiple universities, we have a unique opportunity to test global intrusion detection techniques. Intrusion detection agents, deployed at each campus, can establish secure communication paths across the network backbone to monitor coordinated attacks from multiple locations. Such distributed monitoring is uniquely enabled by the multi-university participation.

4 Project Team and Management Plan

To better manage the multiple objectives of this project, we have sub-divided them into 4 primary components, each of which will be led by a 2-person team:

- **WHYNET framework (Bagrodia & Rao**): The primary objective is to design and implement the architecture to integrate geographically-distributed physical testbeds with the scalable simulation framework. Primary activities will include: design of the interfaces among the multiple components of the hybrid testbed, evaluate effectiveness of the various operating modes, and characterize performance characteristics of the hybrid testbed itself.
- **Physical testbeds (Fitz & Mitra):** These include deployment of the local physical testbeds using MANET technology (UCLA, UCSB, UC Riverside, Delaware), novel radio & channel testbeds (UCLA, USC), and IP-CDMA testbed (UC San Diego). Although the PIs at the corresponding institutions will be responsible for deployment and operations of the testbed, their activities will be coordinated by the team leaders.
- **Repository (Srivastava & Takai)**: WHYNET will generate a rich collection of measurements, traces and models for channel, radio, protocol and application traffic. These will be made available to the larger scientific community via a web-accessible site.
- **Networking research case studies using WHYNET (Gerla & Tripathi):** Single and multi investigator experiments will be coordinated and carried out in a controlled, repeatable environment (i.e., traffic and application scenario, radio platform, radio channel characteristics, motion, relevant protocol layers, etc.). A number of target protocols and applications using WHYNET were described earlier. The results will be filtered and catalogued in the repository.

To facilitate co-ordination, the team leaders will hold monthly teleconferences. We have also scheduled quarterly in person progress reviews to be attended by the project PIs and key personnel. An Advisory Board will be formed to guide the development and subsequent use of WHYNET. The Board will include representatives from Government (NSF, DARPA, NRL, …), industry (Microsoft, Ericsson, ST Microelectronics, HRL, Boeing, …), and the IETF community. We expect the board to hold quarterly meetings that coincide with the PI review meetings, so that appropriate feedback can be provided to the group on an ongoing basis to realign priorities as needed.

It is our intention to make the work products and the tesbed itself accessible to the wireless networking research community. The work products generated from the activities of the testbed will include measurements, traces, models, and implementations, together with results of various studies. These will be made available via a web-based distribution system. We also envisage providing access to WHYNET itself to the research community via appropriate web interfaces. In the first two years of the project, only project members will be able to access the testbed. However to support access by remote project members, we will develop appropriate interfaces to support uploading of models, code implementations, and configuration files via a web-based system. Appropriate resources have been budgeted to both develop the interface and establish a preliminary reservation system for such access. In the third year, we will extend the user community to a few friendly outside users, and make the testbed accessible to the wireless research community during the fourth year. As the testbed matures, we expect to leverage funds from our industrial sponsors and appropriate government agencies to both expand its capabilities and to manage the larger user community that we expect will grow around WHYNET.

Testbed Schedule

Year 1: Complete simulation models for all radio testbeds, and acquire the necessary hardware to build replicas of the existing radios; integrate the CDMA 2000 testbed at UCSD with a physical WLAN testbed at UCLA using SCENIC; deploy a hybrid tesbed at UCLA that integrates ns-2 and QualNet based simulation models with physical WLANs and MANET testbeds at UCLA. Evaluate QoS layer-interactive approaches using the hybrid testbed and report/document the results in the repository. Develop security attack scenarios and test existing countermeasures in the hybrid environment.

Year 2: Deploy cluster of narrowband SDR radios, and the mediumband QAM testbeds and make them accessible to the research community via WHYNET; replicate hybrid testbeds developed in Year 1 at other campus sites including UC Riverside, UCSB, UCD and University of Delaware; integrate the CDMA 2000, WLAN and MANET testbeds with the simulation testbed in WHYNET; make available the first set of measurements & traces from MANET and WLAN testbeds; use the hybrid testbed for studies on Always-Best-Connected service; adaptive transport and streaming protocols, and service discovery protocols. Make scenarios and results available via the repository

Year 3: MIMO testbed, wideband SDR & firmware defined radio testbeds, and UWB testbed all completed and tested; complete system-level performance studies using WHYNET that demonstrate impacts of MIMO and UWB for sensor networks and power-aware networks; test performance of inter-layer aware QoS and network protocols on the new radios; integrate remote MANET, WLAN, CDMA 2000 and wideband radio testbeds into WHYNET. Preliminary access to WHYNET to limited outside users.

Year 4: All radio testbeds integrated into WHYNET. Demonstrate the integration of various degrees of real vs emulated components in the hybrid platform. Evaluate the effectiveness of remotely controlled experiments using the federated testbed. A full set of results and simulation models are available within the repository. Access to WHYNET in production usage by project team members and outsiders.

Project Team

A multi-disciplinary, multi-institution team has been formed to provide the appropriate mix of expertise in the diverse fields that are targeted by this initiative. The team members have substantial expertise in design and management of physical and simulation testbeds (Bagrodia, Gerla, Rao, Takai), development of novel radio technology (Daneshrad, Fitz, Mitra), wireless systems (Mitra, Rao, Srivastava), networking (Gerla, Krishnamurthy, Mohapatra, Royer, Shen, Srivastava, Tripathi) and performance evaluation (Bagrodia, Gerla, Rao, Tripathi). Many of the PIs have worked together on previous collaborative projects from NSF and other agencies. The team's efforts will be considerably enhanced from its partnerships with a number of key industrial players. Team members already have ongoing collaborations with HP (Gerla), Intel (Gerla, Fitz, and others), Ericcson (Rao, Gerla), and Nokia (Royer). In addition, we will work closely with researchers at HRL, Microsoft, ST Electronics, and eXtreme Spectrum as documented in their letters of support.

In addition to previously funded NSF efforts described in the next section, WHYNET will substantially leverage work by the PIs on related projects. For instance, Center for Embedded Networked Sensing (CENS) is an NSF Science & Technology Center at UCLA with participation from UC Riverside, USC, CalTech etc. focusing on wireless sensor network systems and applications. The various testbeds, emulation tools, and wireless sensor node hardware being developed by CENS will be leveraged for WHYNET, an activity that will be facilitated by Srivastava's participation in both CENS and WHYNET. WHYNET will build on significant new activities underway at the California Institute of Telecommunications and Information technology at UC San Diego. Cal-(IT)^2 has received $100 million in funding from the State of California and raised an additional $200 million from non state sources to create new facilities and fund new research and deployments throughout Southern California. Professor Rao's prominent role in both Cal-(IT)^2 and WHYNET will ensure a mutually beneficial relationship among the projects. Similarly, the ONR supported Minuteman project ($12M for 5 years; PI: Gerla) is aimed at developing the future internet-in-the sky for the automated battlefield operation. The Minuteman project also includes a sophisticated wireless testbed with a collection of helicopter- and robot- mounted wireless communication devices. Many of the WHYNET PIs (Bagrodia, Daneshrad, Gerla, Srivastava) are working on the Minuteman project. Lastly, under a grant from the Intel Corporation, Professors Fitz, Daneshrad, Gerla, Srivastava and others are developing an "Experimental Testbed for Research in Advanced Wireless Communications." This project funds the development of hardware and tools for a broad spectrum of project courses in wireless communications and networking, and will be an excellent adjunct to similar teaching application of WHYNET as discussed in section 6.

5 Results from Prior NSF Support

The PIs and key personnel affiliated with this proposal have received substantial prior funding from NSF. We mention only those projects that are particularly relevant to this proposal.

Professor **Bagrodia** is the PI on a Special Projects award titled "iMASH: Interactive Mobile Application Support for Heterogeneous clients" which has produced middleware to support continuous computing [PZB:02, BPG:03]. He is also a Co-PI on "NGS: Collaborative Research: Performance-Driven Adaptive Software Design and Control" (ACI- 0103764) where his group is extending grid software for networks of mobile low-end computing devices like PDAs [PHD:02]. Professor **Srivastava** is the PI on NSF ITR award ANI-0085773 "Technologies for Sensor-based Wireless Networks of Toys for Smart Developmental Problem Solving Environments," (9/00 to 08/03; $1,778,163) which is investigating 'person to physical world' communications in deeply instrumented 'smart spaces' formed by unobtrusively imbedding processors, micro-sensors, and radios in physical objects in the context of a 'Smart Kindergarten'. Selected publications include [CMYea:02], [PLS:02], [SPS:02], [SS:02]. The lab test bed will become a WHYNET component. Professor **Rao** was a PI for "Optimization of Delay Constrained Wireless Communication Networks," $ 880,313, September 15, 1997 to August 31, 2000, a joint award with L. B. Milstein, P. Siegel and R. Cruz. (Grant number NCR-9725568) to study all layers of the protocol stack to determine how to best allocate the end-to-end delay constraint across the various layers. Professor **Daneshrad**'s NSF support has included an equipment grant, (Acquisition of Equipment for An Integrated Wireless Research Laboratory NSF 9977731, 380k) which has been instrumental in training graduate and undergraduate students in the area of integrated circuits and systems. This equipment is shared in the UCLA Integrated Circuits and systems Laboratory, which is shared among 9 faculty. The success of our experimental research and teaching programs both in the area of communications and in the area of state-of-the-art Integrated circuits have been greatly aided by the equipment obtained through the this program [Frig:00, Frig:02, Cab:01, Zou:01]. Professor **Gerla** has been the PI on **"**Scalable Routing and Multicast in Mobile Ad Hoc Wireless Networks" (No. 9814675, 2000-2002, $300K**)** which led to the design of the scalable routing protocols LANMAR and the very robust multicast protocol ODMRP. Both protocols have been presented at MANET IETF working group meetings [KXG:02, XKG:02, LSG:02]. ODMRP is the leading ad hoc multicast protocol today. Another grant for Professor Gerla "High Speed Network Performance Measurements and Analysis", (ANI- 9983138, 2000-2002, $300K) led to the design and implementation of TCP Westwood and related monitoring tools under Linux and FreeBSD UNIX [CGM:01, WVS:02]. Professor **Mohapatra** is a PI on NSF-02339380, "Scalable Software Systems for Large Internet Servers," $441,645, 2003-2006. which involves the experimental design and evaluation of a scalable Internet server environment using functionality distribution as the main theme derived from his work on QoS-aware servers [CM:02, MC:02]. Professors **Mitra** & **Fitz** have a joint grant "Space-time coding for wireless communications" (NSF Award #: CCR-0073505, 10/01/00--09/30/03) which focuses on the development of space-time code designs and decoders for multiuser DS-CDMA signals in realistic channel conditions through the development of meaningful cost-functions for code designs, reduced complexity and adaptive decoder designs and the construction of space-time trellis-coded modulation. Professor **Fitz** is also leading a multi-PI effort titled "An

Experimental Testbed for Research in Advanced Wireless Communications (9809018; $1,472,203)" which developed two software radio testbeds for wireless communication and networking.

6 Training the Wireless Engineer

The UCLA led team is actively trying to change how the training of a wireless communication engineer is accomplished. This proposed testbed can significantly augment that ongoing effort. *In contrast to many projects where education is impacted tangentially, one of the primary goals of this project is the improvement of the education of the wireless engineer by bringing multidisciplinary research into the classroom.*

The future wireless engineer needs significant technical depth to contribute to a rapidly developing technology and significant technical breadth to understand how this technology fits into a market driven economy. Two types of engineers are required: those trained in great technical depth, and those who are trained in "systems" aspects with an in-depth understanding of trade-offs and interactions across layers of a wireless communication system. Currently the standard practice in academia is to have individual faculty work closely with individual students on problems of great technical depth. The current course structure does not produce well trained engineers of the second type. The project team feels strongly that broad systems training can only be accomplished in "hands-on" experimental courses or projects where the students see the tradeoffs involved in real system design. The proposed testbed can enable these types of courses across the curriculum. Even though today wireless is a vertical technology, 4-5 years from now, the most interesting and challenging problems will be those related to wireless systems, so we believe that an inter-disciplinary yet closely-knit engineering program such as ours is well suited for the training of wireless engineer of tomorrow.

6.1 An Educational Testbed Approach

The UCLA led team has a vision of having a set of courses that incorporates both technical depth and a system level perspective. This systems level perspective will be achieved in courses that incorporate significant and sophisticated project based assignments. Sophisticated project based assignments are only feasible if a variety of stable and easily usable building blocks are available to be incorporated into the projects. This stability and ease of use will be critical. Students engaged in project courses typically cannot spend a great deal of time on extraneous components if the solution to the project posed is going to be sophisticated and detailed. One of the goals of WHYNET will be to develop and formalize the sharing of a wide variety of building blocks for project courses in both CS and EE. We envision that the research activities in WHYNET will continually produce resources that can be migrated to the EE-CS curriculum.

Research engineers and technicians will be critical for developing and maintaining this set of shared tools. Faculty are for the most part pulled in many directions by the demands of teaching, research, and service and do not really have focused time to ensure tools remain stable and documented. Students and teaching assistants are by definition transient and are not useful for long-range development and stability. Research engineering support for this consortium is important to sustain an active tool-building paradigm for the wireless communication curriculum.

6.2 The wireless classroom Project

In achieveing our goals, we will seek the synergy with other educational efforts such as the HP Mobility grant and the Intel Wireless grant. The purpose of these grants is to explore the opportunity of enhancing instruction and student collaboration in and out of the classroom using wireless communications. The vision is to establish the **wireless classroom**, namely a flexible infrastructure allowing students to be always connected with classmates, instructors, and research peers through wireless networks of portable devices. Several class projects have emerged during the past year including: video conferencing on PDAs connected with a peer to peer 802.11 network; video session transfer between different devices and; Bluetooth and 802.11 network interconnection. Our future work will establish ad hoc network islands within the Campus, targeting applications such as work group communications, project collaboration and emergency networking. . Collaboration across campuses interconnecting our "ad hoc" classroom testbeds is also planned. This project will allow different teams to share software (e.g., reliable multicast protocols, adaptive video middleware) and also, in the true spirit of mobility, to develop wireless classrooms that go beyond Campus boundaries. The HP project has a high educational value as it trains students in the development of wireless ad hoc network applications. The education project will clearly benefit from WHYNET as protocols and technology produced there are moved into the curriculum. Conversely, the student teams will be ideal first users and testers of WHYNET technology.