High Fidelity Wireless Network Evaluation for Heterogeneous Cognitive Radio Networks

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ABSTRACT

We present a high fidelity cognitive radio (CR) network emulation platform for wireless system tests, measurements, and validation. This versatile platform provides the configurable functionalities to control and repeat realistic physical channel effects in integrated space, air, and ground networks. We combine the advantages of scalable simulation environment with reliable hardware performance for high fidelity and repeatable evaluation of heterogeneous CR networks. This approach extends CR design only at device (software-defined-radio) or lower-level protocol (dynamic spectrum access) level to end-to-end cognitive networking, and facilitates low-cost deployment, development, and experimentation of new wireless network protocols and applications on frequency-agile programmable radios. Going beyond the channel emulator paradigm for point-to-point communications, we can support simultaneous transmissions by network-level emulation that allows realistic physical-layer interactions between diverse user classes, including secondary users, primary users, and adversarial jammers in CR networks. In particular, we can replay field tests in a lab environment with real radios perceiving and learning the dynamic environment thereby adapting for end-to-end goals over distributed spectrum coordination channels that replace the common control channel as a single point of failure. CR networks offer several dimensions of tunable actions including channel, power, rate, and route selection. The proposed network evaluation platform is fully programmable and can reliably evaluate the necessary cross-layer design solutions with configurable optimization space by leveraging the hardware experiments to represent the realistic effects of physical channel, topology, mobility, and jamming on spectrum agility, situational awareness, and network resiliency. We also provide the flexibility to scale up the test environment by introducing virtual radios and establishing seamless signal-level interactions with real radios. This holistic wireless evaluation approach supports a large-scale, heterogeneous, and dynamic CR network architecture and allows developing cross-layer network protocols under high fidelity, repeatable, and scalable wireless test scenarios suitable for heterogeneous space, air, and ground networks.

Keywords: Wireless evaluation, cognitive radio networks, network emulation, situational awareness, heterogeneous networks, cross-layer design, wireless tests and measurements.

1. INTRODUCTION

Wireless network experiments are typically time-consuming to set up and execute in general, and they are hard to repeat because of the highly dynamic wireless environment. Cognitive radio (CR) networks with configurable radios offer several dimensions of tunable actions for spectrum sensing, dynamic spectrum access (DSA) and multi-layer optimization,[1–4] and introduce new challenges for high fidelity test and evaluation. In particular, wireless evaluation of CR networks should provide the flexibility to configure diverse transmission parameters (such as power, rate, channel, scheduling and routing decisions), emulate realistic network effects (such as physical

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channels, topology, and mobility), and provide reliable network measurements (such as link rate, end-to-end throughput, and packet delay).

Field tests can be very costly and delay the initial testing and early prototyping of wireless network technologies. In addition, real field tests are very hard to control and repeat with consistent results across time and space as wireless channels change continuously. In general, there are two basic methods for wireless network experiments before proceeding with field tests: *simulations* and *testbeds*.

Simulations are typically easy to execute with low cost and provide repeatable and scalable experimentation capability for CR networks. However, there are several restrictive assumptions in current simulators, such as modeling irregular transmission regions by unit disk graphs, capturing only the statistical effects of multipath propagation instead of actual ray-tracing, and assuming basic on-off models for licensed user activity, among others. Therefore, pure simulations cannot fully capture physical channel properties for realistic evaluation of wireless network performance.[5]

Testbeds provide realistic wireless evaluation platforms to run protocols directly on hardware with real signal transmissions.[6] However, testbeds are typically limited to fixed topologies and cannot be used to test different dynamic topology and mobility scenarios. A single testbed environment cannot capture all the necessary wireless network characteristics and simulations often fall short from representing the complex signal propagation properties.

One particular challenge in performance evaluation is the diversity of wireless environments, including *space*, *air*, and *ground* networks, aimed for CR network applications. In CR networks, *secondary users* (SUs) sense and dynamically access channels without (or with limited) interference to *primary users* (PUs) with dedicated channels. Therefore, CR networks are designed to perceive, learn and adapt to network dynamics and their functionalities should be evaluated in a controllable and repeatable test environment that can generate different levels of topology, channel and traffic dynamics. The increasing capabilities of CR networks bring up the additional challenge to design a more complex evaluation environment that needs to configure several radio properties and test diverse user classes (PUs, SUs, and jammers) with different device and protocol capabilities.

In this paper, we present a high fidelity *network emulation testbed* that combines the advantages of scalable simulation environment with reliable hardware performance for repeatable evaluation of heterogeneous CR networks that can possibly include PUs, SUs, and jammers. Real signals are sent over emulated channels according to higher layer protocols that are either fed by the simulation environment or directly run over the radio hardware. In particular, we can replay field tests in a lab environment with real radios learning the dynamic environment and adapting their operational parameters for end-to-end goals in CR networks. These field tests may be collected separately or jointly from space, air, and ground networks.

Our CR network evaluation approach goes beyond the test of an isolated protocol (e.g. DSA) and it is not limited to a particular software-defined-radio (SDR) platform. Instead, we test and validate *multi-layer* CR network protocols in end-to-end operation with several dimensions of tunable actions including channel, power, rate, schedule, and route selection. This leads to a fully programmable CR network test environment that can reliably evaluate the necessary cross-layer design solutions with the configurable optimization space.

The underlying hardware experiments represent the realistic effects of physical channel, topology, mobility, and jamming on spectrum agility, situational awareness, and network resiliency in a CR network. We can scale up this holistic wireless evaluation approach by introducing virtual radios that can seamlessly interact with real radios and support a large-scale, heterogeneous, and dynamic CR network architecture. In this setup, CR network protocols can be effectively developed and reliably tested under high fidelity, repeatable, and scalable wireless test scenarios suitable for heterogeneous (space, air, and ground) networks. In this paper, we present our capability to integrate programmable radios with the network emulator and run cross-layer optimization experiments over real radios. In particular, we implement a robust cross-layer approach of joint routing and spectrum allocation and evaluate the dynamic throughput and delay properties of spectrum-agile communications subject to realistic physical channel effects. These test results are more reliable than simulations and more repeatable than static testbeds, and allow fast and cost-effective development of CR network algorithms and SDR prototypes.

The rest of the paper is organized as follows. We introduce the general architecture of CR network testbed in Section 2. Section 3 describes CR network test environment, where the end-to-end network performance is evaluated for multi-hop CR networks and the network statistics are visualized in the custom GUI. Then, Section 4 demonstrates the robustness and adaptivity of the prototype implementation of programmable CR network capabilities in a dynamic network topology. We discuss extensions of CR network test capabilities in Section 5 and conclude the paper in Section 6.

2. COGNITIVE RADIO NETWORK TESTBED

The testbed we developed for CR networks is equipped with versatile and robust simulation and emulation capability to fulfill a broad range of wireless network experimentation needs under realistic physical channel effects. We combine the advantages of low-cost and scalable simulation environment with reliable hardware performance for high fidelity and repeatable CR network testing. We demonstrate the efficiency of the testbed in supporting the cross-layer protocol stack in CR network scenarios with real RF nodes (SUs) and virtual simulated nodes (PUs and jammers). The CR network testbed, shown in Figure 1, consists of

1. Radio Frequency Network Emulator Simulator Tool, RFnest™,[7] developed by Intelligent Automation, Inc. (RFnest™is a trademark owned by Intelligent Automation, Inc.),
2. software simulator running on a PC host,
3. configurable RF front-ends, and
4. digital switch.

RFnest™provides robust control of the attenuation levels on wireless channels. We have analog and digital versions of RFnest™with attenuator box and FPGA implementations, respectively, to control physical channels. Here we report our testbed results based on analog version that supports up to four programmable radios (wireless nodes), each running on embedded Linux. These radios are connected via RF cables to the network emulator, RFnest™, that supports a fully connected network with digitally controlled channel impulse responses. Note that this is not a point-to-point physical channel emulator that can control properties of a single channel but further supports simultaneous transmissions of multiple nodes with signal-level interference to each other. RFnest™allows real radios (configurable RF front-ends) to send real signals over emulated channels. In addition to analog RFnest™, the digital version can further scale up the evaluation by seamlessly integrating software-controlled virtual nodes into the scenario.[7]

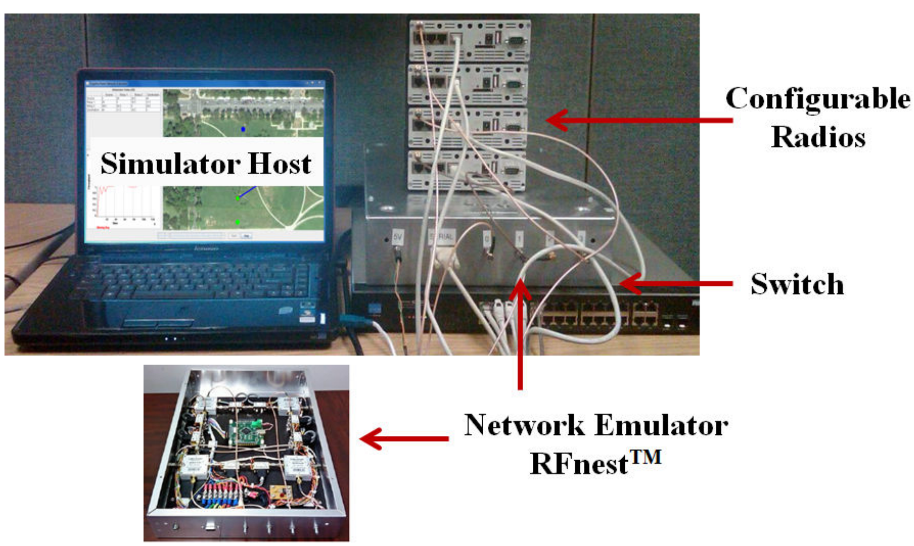

Figure 1. CR network testbed setup with RFnest™.

Figure 2. Network emulator, RFnest^{TM}(4-node analog version).

Integrated with a software simulator, our testbed allows efficient and reliable experimentation of new wireless protocols at real commercial radios that can be readily used in field tests. Without deploying any static testbed, we can test realistic physical channel effects for different simulated topology and mobility scenarios in CR networks. The testbed environment presented in this paper reduces the cost and implementation time of CR network development and SDR prototyping with cognitive capabilities by

1. testing the CR network in a controlled, repeatable and realistic environment with the same radios used in the actual deployment,
2. employing a hybrid software/hardware network emulator with high fidelity model for testing, and
3. providing a tool that can replay a field test with all its complexity in a lab environment.

In general, RFnest^{TM}-based CR network testbed can configure transmission power, rate and channel/frequency selection, can emulate physical channels, topology, and mobility effects, and can measure link rates, end-to-end throughput, and delay. The parameter space is bound to the inherent capabilities of RF front-ends. In this paper, we utilize programmable radios to test CR network capabilities, although the same setup can be used with other SDR platforms.

2.1 Physical Channel Emulation in Wireless Networks

The analog version of network emulator, RFnest^{TM}, is shown in Figure 2. The hardware module is attached to a standard transceiver and communicates with the simulation server to receive the parametric model of signal power, channel impulse response, and interference parameters. First, the physical layer simulation component digitally controls the hardware module to connect nodes with the necessary attenuation. Then, signals travel on RF cables through an attenuator bank. The network emulator consists of four real nodes and can emulate a broad range of 2-D and 3-D network topologies and mobility effects. CORE (Common Open Research Emulator)[8] is used to manage the scenario being tested, create the emulated virtual nodes, and configure EMANE (Extendable Mobile Ad-hoc Network Emulator),[9] allowing the user to move nodes via the GUI, and configuring the routing and other network behaviors on both the real and virtual nodes. In this paper, we demonstrate our test capabilities with the 4-node analog version of RFnest^{TM}. We also have a digital version of RFnest^{TM}, a 12-node network channel emulator on a Xilinx virtex 4 FPGA, that we will discuss later in Section 5.

2.2 Topology and Mobility Emulation

In addition to individual physical channels, we can emulate different network *topology* and *mobility* effects. With the interactive GUI, we can move nodes manually or the mobility can be automatically adjusted according to

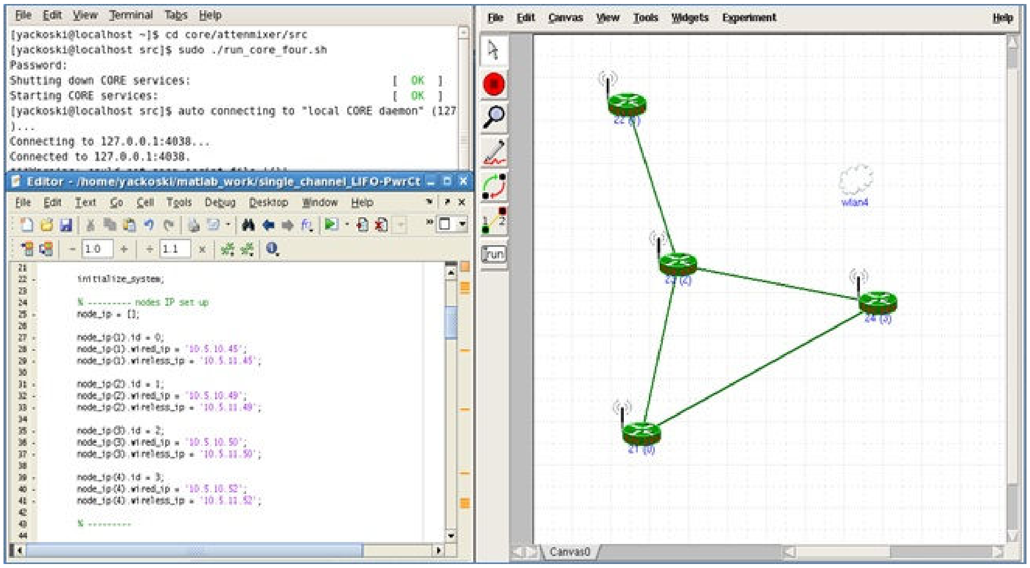

Figure 3. Node IP setup and CORE GUI.

field test results or random mobility models. We can also emulate group mobility. For that purpose, we can consider different groups of nodes, each connected to one port of the attenuator, and nodes within each group are connected with fixed attenuators. The simulation component can digitally control the hardware module to reflect how the mobility of groups changes the channels between different groups. Then, using the channel information, the attenuator bank varies the attenuation between different node groups thus generating different multipaths and emulating a broad range of dynamic topologies and group mobility effects.

3. HARDWARE EXPERIMENTATION OF COGNITIVE RADIO NETWORKS

We demonstrate the CR network testbed capability with an emphasis on the robustness and adaptivity of the CR prototype implementation in a *dynamic* network topology. We test a robust *cross-layer* optimization approach of joint routing and spectrum allocation and evaluate the dynamic throughput and delay properties of spectrum-agile communications subject to realistic physical channel environment. We integrate programmable radios with the network emulator, as shown in Figure 1, and run cross-layer optimization experiments over real radios.

3.1 Configurable/Programmable Radios

We use configurable radios from Ubiquiti. The hardware has a built-in firmware, called `OpenWrt` that allows us to customize the device by using different packages. In our testbed setup, we use the Ad-Hoc mode to configure the device as an ad hoc node in the network. The radio has one RF port and 4-Port Gigabit Ethernet interface. The RF port is connected to the wireless network emulator via RF cable, and one of the Gigabit Ethernet ports is used to configure the radio.

We use `Madwifi`,[10] an open source IEEE 802.11a/b/g Linux driver, to configure the radio with desired physical layer parameters. There are 53 channels available for adaptive spectrum configuration. Specifically, there are 13 channels with center frequencies from 2.412GHz to 2.472GHz, with 5MHz bandwidth for each channel, and 40 channels with center frequencies from 5.18GHz to 5.6GHz, with various per channel bandwidths. Each radio can select 8 transmit power levels from 0dBm to 16dBm, and 12 transmission rates from 1 Mbit/s to 54 Mbit/s. For the received signal strength indicator (RSSI) and throughput measurements, we remotely access the radios, specify the transmitter and receiver IPs, configure UDP data streams, execute `iperf` (an open source performance evaluation software), and read the `iperf` and `iwconfig` (or `associated_sta`) reports from the radios to the simulator host. We configure each radio with two IP addresses: one for wireless card (RF port), and the other for the Ethernet interface, as shown in Figure 3. We connect each wireless card of the radios via

RF cables to the RFnest™. The radios are connected with the host via Ethernet over the switch, so the host can configure the radios to the desired frequencies, transmit powers, and rates.

3.2 Network Measurements

We developed the capability to measure the end-to-end *throughput* and *delay* for real radio transmissions. The measurements are collected with `iperf`. For that purpose, we first remotely access the radios from the host, specify the wireless IPs of transmitter and receiver, configure UDP data streams, execute `iperf`, and finally read the `iperf` reports from the radios to simulator, as illustrated in Figure 4.

The throughput and delay measurements pose two basic challenges for implementation:

1. The network is distributed and each radio has its own clock, i.e., the network is an asynchronous system. Therefore, we build the capability to trace the packet delay at each hop (with different clocks) along the path and measure the end-to-end packet delay.

2. The time consumed for communications between the host and radios (that includes the radio configuration time, the `iperf` execution time for throughout measurement and channel estimation) is non-negligible compared to the end-to-end delay. Our measurement experiments reveal the latency between the host and radio communication on the order of milliseconds.

We measured and excluded these latency factors in performance evaluation when measuring the end-to-end delay and obtained the reliable delay measurement that includes data communications and control information exchange only. We generated a system clock in the network simulator which excludes the time consumed for communications between the host and radios (that includes the radio configuration time, and the `iperf` execution time for throughput and channel measurements).

CR network operation must be agile to changes in spectrum availability. Therefore, it is essential to estimate and track the channel conditions. As shown in Figure 4, *channel estimation* lets every node transmit separately to each neighbor, collects RSSI measurement and feeds it back to higher layers thereby adapting the cross-layer spectrum allocation, power control and routing mechanisms to channel dynamics. We track the time-varying physical channels by running channel estimation along with all cross-layer design decisions.

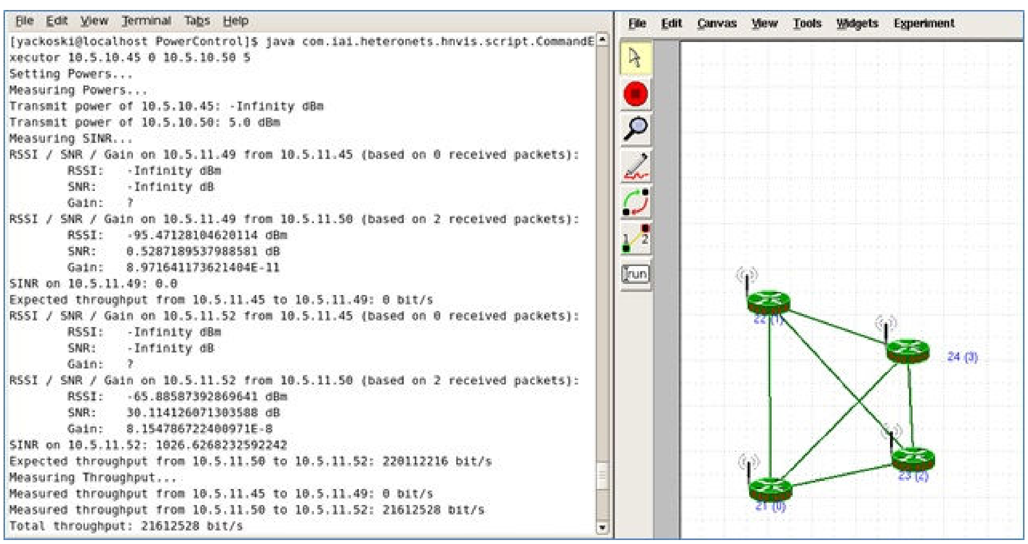

Figure 4. Channel measurements.

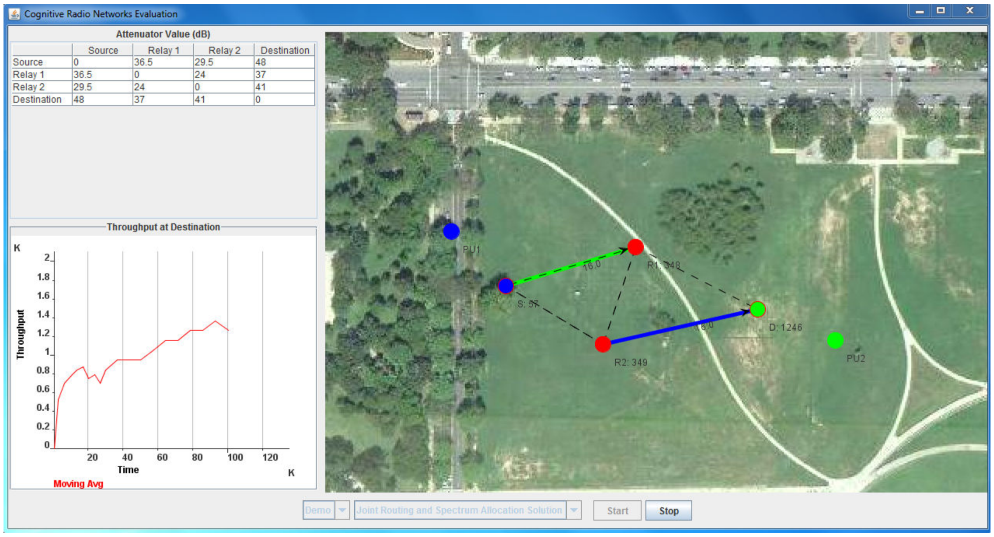

Figure 5. CR network testbed GUI showing spectrum and route allocation scenario 1.

3.3 Interactive CR Network Testbed GUI

The network statistics can be collected and visualized in the custom GUI (as shown in Figure 5) where we evaluate the end-to-end network performance for multihop CR networks. The upper left part of GUI shows the table of attenuation values (in dB) between all node pairs. As nodes move in GUI, channel estimation monitors attenuation values and update the table in real-time. The lower left part of GUI shows the moving average of the end-to-end throughput (delivered to the destination) over time. When we first activate nodes, queues start building up and packet rate starts increasing. Then, the throughput saturates to a point and further fluctuations are due to random channel and queue events. In addition to throughput performance, we also have the capability to measure and visualize packet delay performance (both in terms of average packet delay and hard packet deadlines).

The right side of GUI shows the network topology. The two PUs on the edges are colored blue and green denoting two dedicated channels. Each SU is colored blue or green depending on which PU they interfere with. If they do not interfere with any PU, then they are colored red. The dashed lines between nodes represent the possible connectivity. Whenever a link is activated, it is colored blue or green depending on which channel is assigned to this link. The instantaneous queue backlog is shown next to each node and the instantaneous channel rate is shown under each activated link. Nodes can be moved manually or automatically either playing a field test or according to a random mobility model.

4. DEMONSTRATION OF COGNITIVE RADIO CAPABILITIES

We used our CR network testbed environment to evaluate different CR network scenarios and protocols ranging from spectrum sensing to DSA. Here, we describe the testbed evaluation of cross-layer design in CR networks. As illustrated in Figure 6, a CR network consists of PUs with dedicated channels and SUs opportunistically seeking access to PU channels. The static allocation of licensed spectrum allocation is inefficient in terms of resource utilization.[11] In spectrum-aware CR paradigm, SUs sense and access channels, whenever there is no PU activity. Then, the spectrum occupancy with the available frequency bands becomes location dependent and therefore requires joint design of dynamic spectrum access with routing in multi-hop CR networks.[12, 13]For that purpose, SUs need to discover spectrum holes and adapt to dynamic wireless environment through spectrum sensing and channel estimation. Then, SUs need to allocate spectrum through power/rate control and frequency adaptation along with routing decisions in a cross-layer design framework. In the meantime, SUs should avoid possible interference with PUs and route packets around areas with heavy interference, fading, noise, congestion and jamming. To support flexible operation, routing and spectrum allocation should be designed jointly to

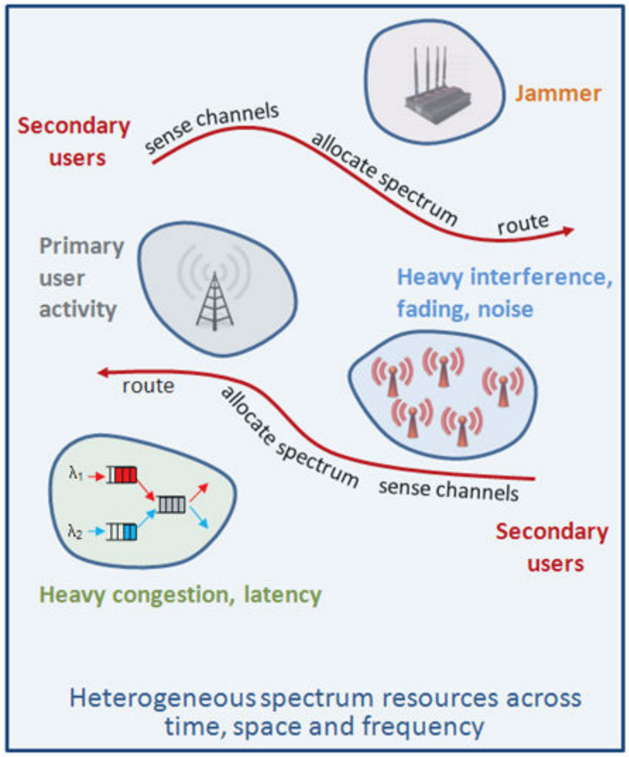

Figure 6. Dynamic CR network operation with heterogenous user classes.

optimize network performance in a distributed setting without centralized control. This cross-layer optimization framework will quickly adapt to network dynamics and provide a robust solution across the network stack.

In this paper, we demonstrate how to evaluate joint routing and dynamic spectrum allocation in CR networks. Specifically, we integrate physical channel-awareness in optimizing cross-layer protocol stack, where the spectrum, power, rate, and channel allocation decisions are made jointly with the next hop selection for routing. In the meantime, transmissions are coordinated for medium access control. This is a spectrum-aware networking scenario, where we show the effects of PUs on CR network performance.

We demonstrate how SU nodes with cognitive capabilities adapt their transmission power, channel selection, and packet routes to dynamic spectrum availability. This shows the ability of the physical layer resource allocation (frequency selection and power/rate allocation) and dynamic routing protocols to adapt to link failures caused by PU activities, jamming attacks, and topology changes.

We build and test a CR network with the following capabilities:

1. spectrum sensing,
2. channel estimation/tracking,
3. neighborhood discovery,
4. transmission (link) scheduling,
5. route selection (e.g., backpressure routing,[14] network coding[15]),
6. frequecy/channel selection,
7. transmission rate adaptation,

Figure 7. CR network testbed GUI showing spectrum and route allocation scenario 2.

8. transmission power control.

The network statistics can be collected and visualized in the custom GUI so that we can evaluate the end-to-end network performance for multi-hop CR networks. We demonstrate the throughput and delay performance under different scenarios. The actual throughput measured from real radios is used for queue updates, and physical channels are estimated and tracked in real time by measuring RSSI for all transmitter-receiver pairs (from CORE).

We tested different scenarios on our network emulator and demonstrated the spectrum awareness of the implemented solution for CR networking. Figure 5 shows a scenario, where the source and destination nodes are within the interference range of PU 1 and PU 2, respectively. The packets are forwarded from the source node to relays using channel 2 (green) only, as channel 1 (blue) is not available at source node. Then, relays switch from channel 2 (green) to channel 1 (blue) and forward packets to the destination, as channel 2 (green) is not available at the destination. This demonstrates the capability of adaptive channel selection along the multihop path from the source to the destination.

As shown in Figure 7, where both PU 1 and PU 2 are active on channel 1 (blue) and channel 2 (green), respectively. Relay 1 is within the interference range of active PU 1 and can only use channel 2 (green). Similarly, relay 2 is within the interference range of PU 2 and can only use channel 1 (blue). Both source and destination nodes do not interfere with PU 1 or PU 2, thus they can use either channel 1 (blue) or channel 2 (green). The two possible routes in this scenario are through relay 1 using channel 2 (green) and through relay 2 using channel 1 (blue).

As the source moves towards PU 1 (into the interference range of PU 1 in this case), as shown in Figure 8, channel 1 (blue) becomes unavailable for source node. Note that in the previous scenario, shown in Figure 7, source node uses the available channel 1 (blue). With adaptive channel allocation, the spectrum-aware solution enables source node to switch from channel 1 (blue) to channel 2 (green).

By integrating the asynchronous neighborhood discovery algorithm, the implemented solution provides the flexibility to call for neighborhood discovery to initialize the network as well as to adapt whenever the network changes, e.g., due to mobility or node failures. Joint channel allocation and routing are performed with the information of neighborhood and channel availability that is continuously updated.

We can also introduce *jammers* to network evaluation scenarios. There is a growing need to consider harsh RF environments; however it is often difficult to test scenarios with jammer because they may unintentionally interfere with some other transmissions over the air and it may be difficult to get approval for such field tests.

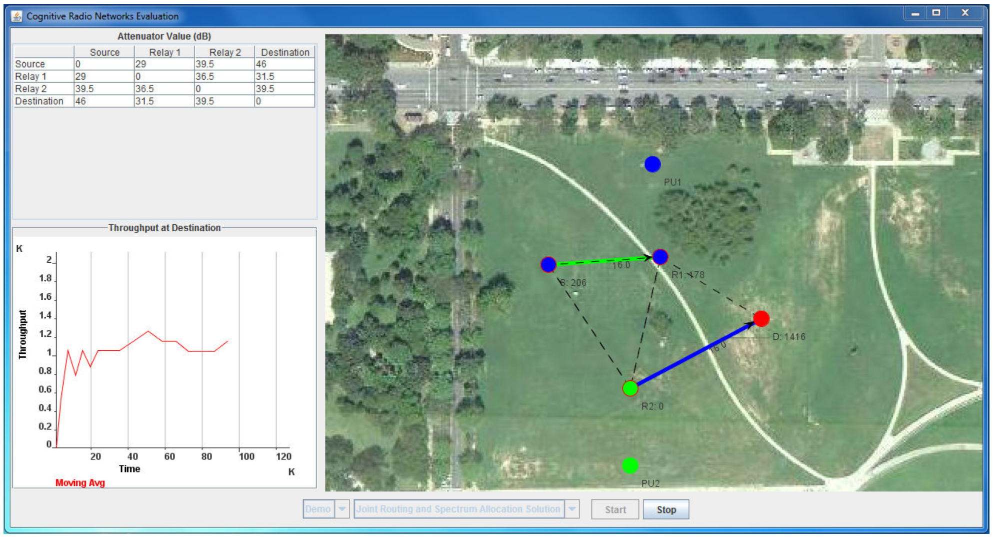

Figure 8. CR network testbed GUI showing spectrum and route allocation scenario 3.

Also, it will be infeasible to re-run field tests and evaluate performance in different RF conditions. On the other hand, simulations can fall short of modeling the impact of different emitters in real RF environments. With the wireless emulation capability of RFnest$^{\text{TM}}$, we can add any emitter in the lab environment and the signals of these emitters will be confined to RF cables so there will be no jamming over the air. If some field tests are available, RFnest$^{\text{TM}}$can create the same channel conditions as the field test and then we can add jammers to the network environment and re-run the scenario with emitters added.

From the SU point of view, a jammer has the same effect as a PU and prevents the SU from transmitting at a specific location on a specific channel. However, there are several differences between a jammer and a PU in terms of possible interference effects and their dynamics. First of all, PU information is either broadcast to SUs or sensed by SUs such that SUs know or predict if a channel is used by a PU, whereas a jammer may suddenly occupy a channel. Second, the arrival and departure patterns of PUs and jammers may be different; jammers may have (often intentionally) arbitrary patterns that cannot be predicted over a short time-scale. Finally, jammers may adapt and change channel allocation strategies while SUs are adapting their own strategies for routing and spectrum allocation. It is challenging to set up a testbed with jammer evaluation in a controlled environment, and therefore it is more realistic to replay previous jamming attack instances from security logs. The physical channel properties of these jamming effects can be readily tested via RFnest$^{\text{TM}}$and jamming-resistant CR network techniques can be developed and evaluated in our CR network testbed.

5. EXTENSIONS OF COGNITIVE RADIO NETWORK TEST CAPABILITIES

In this paper, we showed the integration of our network emulation testbed with programmable radios to test and validate CR network capabilities. Similarly, we can use SDR platforms as RF front-ends and connect them to RFnest$^{\text{TM}}$. A particular SDR platform of interest is based on GNU radio[16] and Universal Software Radio Peripheral (USRP2)[17] that can provide additional capabilities of full programmability at the physical, MAC, network, and transport layers to enable cross-layer design and optimization through a shared control plane. This programmable platform can be further used as the basis to assess the performance of the state-of-the-art DSA schemes and has the potential of allowing for rapid prototyping and testing of new algorithms with minimal hardware dependencies. In general, SDR results in actual CRs are ahead of their model counterparts. Therefore, instead of using model-based simulation, it is more realistic to use actual SDRs in an emulated environment as the reliable path for CR evaluation.

In addition to analog version of RFnest$^{\text{TM}}$, we built and tested a digital version of RFnest$^{\text{TM}}$, a 12-node network channel emulator on a Xilinx virtex 4 FPGA. The digital network emulator, has the following specifications: 1) 132 half duplex wireless channels, 2) Per-channel bandwidth of 20MHz, 3) 3 tap delay line per channel,

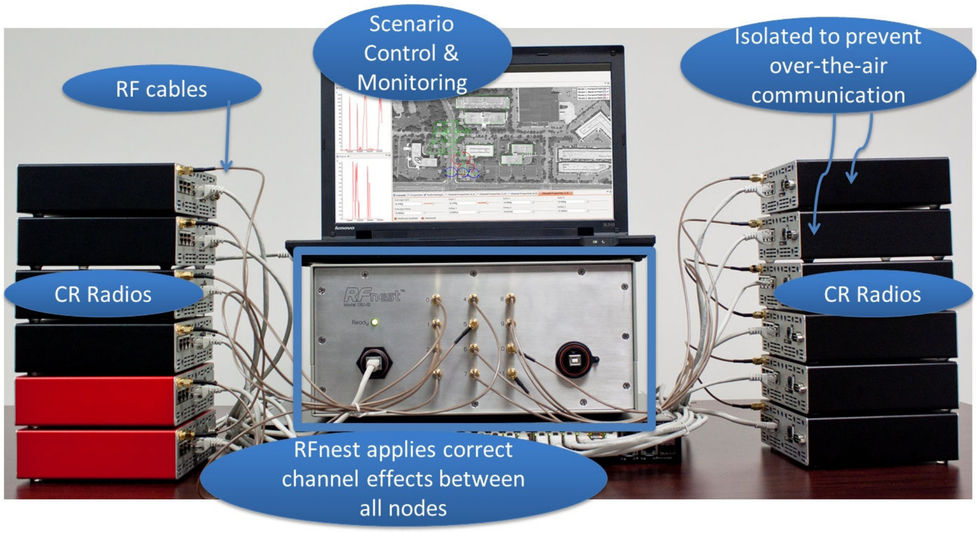

Figure 9. RFnest$^{\text{TM}}$testbed (digital version).

4) Maximum Tap Delay of 16ms, 5) Sample resolution of 12 bits DAC, 10 bits ADC, 6) Output dynamic range of 50dB (digital) + 20dB (analog), 7) Configurable per-channel delay, 8) Modeling of AWGN, Rayleigh and Rician channel. The network emulation testbed capability we built with digital RFnest$^{\text{TM}}$is shown in Figure 9.

Digital network emulator will be useful in CR network experimentation for two main purposes:

1. **Scalability**: We can increase the size of the network by adding virtual nodes that can coexist with real nodes through the signal-level interactions.[7] This will allow signal-level interactions between PUs and SUs, and facilitae realistic evaluation of spectrum sensing and data transmission in CR networks. The design challenge is to separate the network into real and virtual nodes. In general, real nodes should represent the bottleneck nodes under heavy interference in harsh wireless environments.

2. **Mobility**: Analog emulator allows dynamic topology and mobility realizations in terms of signal attenuations but cannot reflect the effects of mobility on the physical channel properties. Digital network emulator provides the digital control capability through FPGA board. This helps adding delay to wireless transmissions and emulating physical channel characteristics including multipath and Doppler effects under diverse dynamic topology effects and possible 2-D and 3-D mobility patterns.

With increasing network test size, we can then emulate both PUs and SUs with physical layer interference to each other thereby facilitating the transition from "white space" with interference avoidance to "gray space" with interference tolerance in CR networks. In this context, digital version of RFnest$^{\text{TM}}$provides the necessary scalability by combining virtual nodes with real radios in a seamless physical-layer interaction environment.

6. CONCLUSION

We presented a high fidelity network emulation approach for controllable and repeatable wireless network evaluation of diverse CR network scenarios for air, ground, and space networks. With these fully programmable emulation capabilities, we can support signal-level CR user interactions, and test different topology and mobility effects. We integrated programmable radios with network emulator, RFnest$^{\text{TM}}$, and provided the configurable test environment to adapt power, rate, scheduling and routing decisions to spectrum dynamics. We demonstrated the CR network testbed via hardware experiments with real radios and tested cross-layer optimization techniques in CR networks. The reported performance evaluation capabilities aim to make CR network prototyping faster and bridge the theory and practice in CR network design, analysis, and deployment under realistic physical channel effects.

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