A Software Defined Testbed for Reconfigurable Antenna Cognitive Radio

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***Abstract*—A cognitive radio is capable of sensing local radio conditions and adapting its transmission and reception parameters to optimize performance in the evolving network environment. The use of software defined radio (SDR) to make communications more flexible has greatly facilitated the design of cognitive radios, by making communications reconfigurable at lower layers of the networking stack. The Cognitive Antenna Testbed described in this paper augments the flexibility of physical layer design through the use of reconfigurable antennas, which are capable of adapting frequency, pattern and polarization electrically, thereby expanding the design space of cognitive radio and networking algorithms. This testbed offers a platform for developing and field-testing reconfigurable antenna algorithms. Representative results of experiments performed with this testbed for antenna state selection, are provided to illustrate its relevance to cognitive networking research. Current research adapting this technology for use in dynamic spectrum access (DSA) applications is also discussed.**

I. INTRODUCTION

Cognitive radio is an emerging wireless communications technique that allocates scarce radio spectrum intelligently to increase the reliability and spectral efficiency of data transmission. Cognitive radio builds upon the flexibility in physical layer algorithm implementation delivered by Software Defined Radio (SDR) to include assessment of, and adaptation to, the surrounding radio environment. While there is a tremendous amount of research in the algorithmic and protocol aspects of cognitive radios, very little attention is given to the antennas used in cognitive links. This paper focuses on the enhancement of an existing SDR [?] platform to enable functionality for cognitive networking enhanced by electrically reconfigurable antennas. These compact form factor antennas are capable of dynamically adjusting their radiation patterns and operating frequency in response to the needs of overlying communication link and network. Fig. 1 shows a graphical overview of our Cognitive Antenna Testbed, and demonstrates the structure of the rest of the paper.

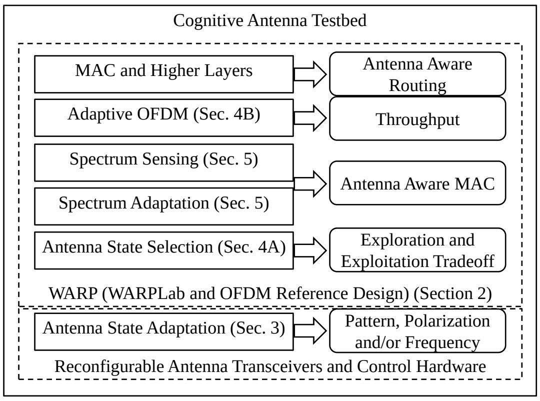

Fig. 1: Overview of Cognitive Antenna Testbed

Electrically reconfigurable antennas have been proposed as a means of mitigating interference and improving link quality [?,2]. These antennas can vary in nature from compact, highly directive beam-steering devices [2] to more omnidirectional antennas that exploit pattern diversity [3]. Previous work with our tesbed has demonstrated the use of a reconfigurable beamwidth and scanning array using leaky wave metamaterial antenna techniques for individual MIMO links [?,8]. Other pattern reconfigurable antennas, that make use of PIN-diodes to alter their radiative structure, have been proposed [1,3]. The Cognitive Antenna Testbed has demonstrated utility in using these

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antennas to improve throughput and minimize packet errors [9,11]. Additionally, reconfigurable antennas have been suggested for tunable multi-band front ends which make them relevant for dynamic spectrum access (DSA) applications. In similar fashion, these antennas alter the radiative structure of the antenna through the use of pin-diodes, MEMS switches, or laser diodes [4]–[6]. These antennas offer promise for the purposes of cognitive DSA, but their integration with existing communications architecture remains to be completed. Integrating and demonstrating these new antenna technologies with practical cognitive networking algorithms is the primary contribution of the Cognitive Antenna Testbed.

II. COGNITIVE ANTENNA TESTBED

As shown in Figure 1, the Drexel Cognitive Antenna Testbed is composed of the Rice WARP Testbed [**?**] with custom software, coupled with external reconfigurable antennas and associated control hardware. WARP hardware consists of two major components: digital baseband processing and analog RF processing. The digital baseband processing is all done on the WARP FPGA board which houses a Xilinx Virtex II Pro (or Virtex 4 in newer versions) FPGA for all digital baseband PHY and MAC layer functionality. The FPGA board has four sets of connectors that provide a set of digital connections for up to four daughter-cards for the 2.4 and 5 GHz ISM bands. Control of external reconfigurable antenna hardware is accomplished through general purpose I/O. The antenna control hardware is generic, allowing for the control of a wide variety of electrically reconfigurable antenna prototypes.

Along with the hardware, Rice University has provided a set of reference designs including an OFDM PHY layer and various MAC layer protocols. In real-time mode, the WARP boards connect via Ethernet to computers and act like a wireless Ethernet bridge, completely transparent to the host. To this system, we have developed and integrated IP cores for real time control of external reconfigurable antennas. In order to provide cognitive antenna networking functionality, the system requires a mechanism to get information regarding the channel state to upper layers to adjust various control mechanisms. Modifications to the design include the addition of a shared memory block to record channel estimates that can be accessed by the MAC implementations.

WARP can be run in a non-real time mode using a Matlab interface known as WARPLab. This system provides the ability to quickly develop PHY layer algorithms in MATLAB, and use the FPGA as a simple buffer. Using this method, all nodes are connected through an Ethernet hub to a centralized controller that provides processing, control, and synchronization to all of the nodes. External reconfigurable antenna control is also possible through this mode allowing for the rapid prototyping of new cognitive antenna algorithms.

While WARPLab is not an ideal mechanism for cognitive antenna networking (due to its non real-time nature) it provides greater flexibility, allowing much finer control over the PHY properties. For cognitive antenna networking research we have extended the WARPLab framework to include functionality that will allow it to operate outside of a centralized controller, as well as a MAC layer implementation. Specifically, the WARPLab framework has been modified to include a packet detection IP core to remove the need for centralized coordination as well as modified to include custom MAC and routing layer implementations. Both of these modifications have aided the development of cross-layer algorithms for cognitive antenna networking.

III. COGNITIVE DESIGNS IMPLEMENTED

This section describes two representative uses of the Cognitive Antenna Testbed for cognitive networking applications. Machine learning approaches to antenna state selection is discussed first. Next, a description of integrated antenna state and rate-adaptive OFDM signaling is presented.

A. Machine Learning

Potential gains provided by the agility of reconfigurable antenna systems can only be realized through state selection techniques which intelligently manage the tradeoff between state exploration and exploitation. The performance of individual reconfigurable antenna states varies with changes in the operating environment such as fluctuations in channel conditions, node mobility, or interference. Any state selection scheme must account for these changes in order to maximize performance of the reconfigurable antenna system by reducing the time spent in suboptimal states. Additionally, the state selection scheme must rely on simple metrics so as to reduce the impact of increased overhead and feedback requirements [8].

Existing selection techniques attempt to strike a balance between state exploration and exploitation by performing periodic exhaustive training over available antenna states. At the conclusion of the training period, the state which performed best over this interval is exploited for a predetermined number of transmissions [9,10]. The use of exhaustive training increases overhead and and results in performance losses due to data transmissions made using suboptimal states.

A state selection technique developed by the authors in [8] employs an online learning framework which seeks to learn the optimal state for a given environment without prior information about each antenna state and without the need for periodic exhaustive training or eliminating states available to the system. The selection process is formulated as a multi-armed bandit problem [**?**,**?**], a mathematical framework designed to learn unknown variables [8]. Traditionally, the multi-armed bandit problem seeks to maximize the reward obtained from a set of decisions which yield random rewards which are $i.i.d$ with a distribution of unknown mean. In the context of reconfigurable antenna state selection, the goal is to design a policy for selecting a state for each data transmission that maximizes the total expected reward in the long run.

Each time a particular antenna state is used, the system gains further insight into the reward distribution for that state and over time, the system can make informed decisions on which states to use for future data transmissions. The MAB framework has an built-in mechanism for managing the tradeoff between state exploration and exploitation making the framework particularly appealing for antenna state selection. In order to evaluate the performance of the online learning framework, experiments were conducted in the Drexel University Bossone Research Center using four WARP nodes each equipped with a Reconfigurable Leaky Wave Antenna (RLWA) [2]. The locations of each node can be seen in Fig. 2 and were chosen to accommodate a combination of LOS and NLOS links. Each node was configured using the WARPLab development environment and designed to operate with a 2×2 MIMO OFDM-based physical layer. Each node was allowed to broadcast 200 packets for all combinations of antenna states between the designated transmitter and the other nodes in the network. Each receiver then collected and stored link information including channel and post-processing signal-to-noise ratio (PPSNR) estimates for post-processing.

Fig. 3 shows results of the average reward for three upper confidence bound (UCB) MAB policies (UCB1, UCB1-Tuned, ϵ-GREEDY) [**?**,8]. The average reward is a measure of the PPSNR achieved over 200 transmissions between Transmitter 4 and Receiver 2 in Fig. 3. For comparison, the upper bound is also plotted and represents a policy which has prescient knowledge and selects the antenna state that will maximize PPSNR for each transmission. The UCB1-Tuned and the UCB1 algorithms were able to match the optimal configuration selected by the upper bound for 90% and 95% of the transmissions, respectively. The ϵ-GREEDY algorithms, which include a mechanism for random state exploration designed to track large changes in state reward distributions, were able to match the optimal configuration 90%, 84%, and 81% for random exploration rates of ϵ = 0.05, 0.1, and 0.2, respectively. These results show that MAB algorithms are viable techniques for reconfigurable state selection and do not require performance limiting features such as periodic exhaustive training, available state space reduction, or *a priori* knowledge of antenna state performance.

B. Joint Antenna Configuration and Rate Adaptive OFDM

The Cognitive Antenna Testbed has been used for testing of joint antenna selection and rate adaptation algorithms for MIMO ad hoc networks. Specifically, it has been used to demonstrate the utility of two different reconfigurable antenna designs in experimental communications scenarios.

1) MIMO Point to Point Links: The first scenario considered 2×2 MIMO links with 2-state reconfigurable antennas used for each element in the transmit and receive array, in both LOS and

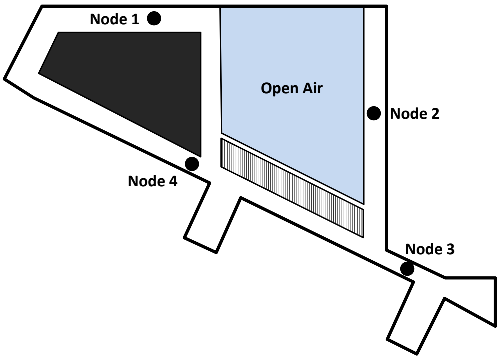

Fig. 2: Node positions on the 5th floor of the Drexel University Bossone Research Center.

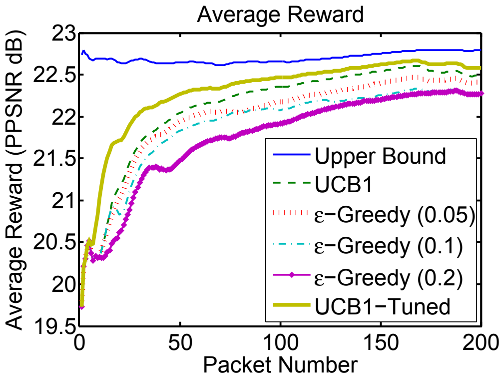

Fig. 3: Average reward for each algorithm for the link between Transmitter 4 and Receiver 2

NLOS environments [9] in a network without external interference.

The antenna selection algorithm is based on estimation of link capacity for each mode configuration via repeated sensing of the channel. The two stage selection algorithm first trains the MIMO channel for each mode configuration through a single packet transmission. Capacity as well as mode configuration and PPSNR, the ratio of signal power to mean squared error vector magnitude for the whitened received data, are stored for each training set. The antenna algorithm is selected that maximizes capacity. Since the number of configurations is minimal the search for optimal antenna configuration can be performed exhaustively with minimal overhead.

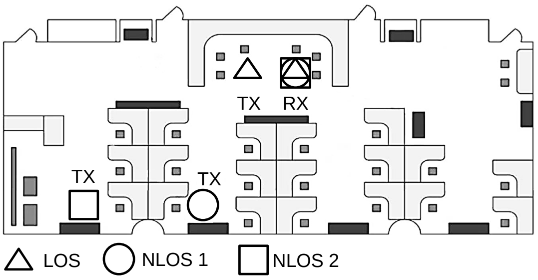

Fig. 4: Link topology for experimental validation of joint configuration/rate adaption algorithm

Position	Metric	Fixed	Reconfig.
LOS	PER data rate (Mbps)	0.22% 21.19	0.34% 22.76
NLOS1	PER data rate (Mbps)	0.06% 11.66	0.03% 21.29
NLOS2	PER data rate (Mbps)	15.4% 6.60	0.84% 11.95

TABLE I: Performance comparison of reconfigurable antenna selection to non-reconfigurable antennas in LOS and NLOS scenarios

In addition to selecting the optimal antenna configuration, the rate of each packet is optimized based on estimation of the achievable data rate given the euclidean distance between each symbol point with normalized power in cartesian space, and the noise power estimated from the PPSNR.

This selection algorithm was evaluated experimentally with the Cognitive Antenna Testbed. The link topologies can be seen in Fig. 4. While results indicated little benefit in LOS scenarios, considerable improvement was demonstrated through the use of the joint algorithm in NLOS scenarios, as shown in Table I.

2) MIMO Ad Hoc Networks: Unlike the first scenario considered, this scenario evaluates the effects of antenna selection in interference constrained MIMO Ad Hoc networks [11]. Experimental evaluation was performed for a three link topology, where each node makes use of a 2-port reconfigurable circular patch antenna. The node topology can be seen in Fig. 5.

The added complexity of modeling interference in the network requires estimation of interference channels as well as the channel of interest. After training is performed to estimate each channel the transmit and receive antenna configuration is selected that maximizes multi-user capacity for each link. After the mode configurations have been

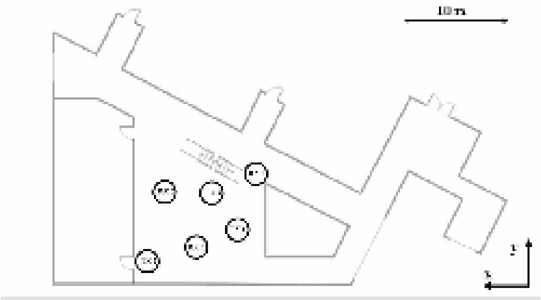

Fig. 5: Link topology for experimental validation of joint configuration/rate adaption algorithm in ad hoc networks

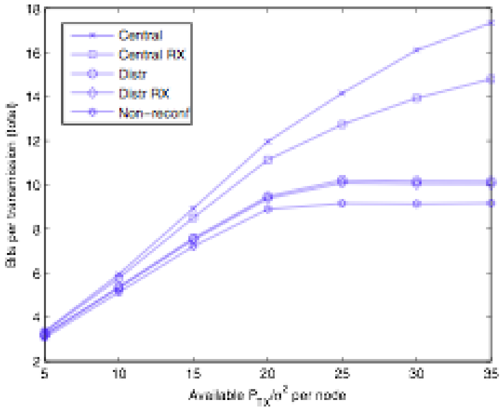

Fig. 6: Performance of antenna configuration and rate adaptation in ad hoc networks for circular patch antennas

selected for all antennas, bit loading is performed on a link by link basis to maximize throughput. A centralized and distributed approach to this optimization is provided in [11].

Results measured for the topology shown in Fig. 5, can be seen in Fig. 6. Result indicate that the use of reconfigurable antennas can provide improved throughput and interference mitigation under both centralized and distributed regimes.

IV. COGNITIVE DESIGNS IN DEVELOPMENT

As mentioned previously, reconfigurable antennas have been considered as a means of providing additional channel figiltering for dynamic spectrum access. The proposed architecture for these radios is one in which a wide band sensing antenna is used for spectrum sensing and opportunity identification, while a re-tunable narrow band antenna is used for dynamic access. While these antennas offer promise for use in deployment with cognitive radios, considerable work must be done to develop the control algorithms for these antennas and integrate their use in to existing networking stack architectures. Additionally, the use of pattern and polarization reconfigurable antennas for the purpose of expanding the spectrum opportunity space to include opportunities in angle, space, and polarization have not been considered as thoroughly.

Spectrum sensing is to the process by which the radio becomes aware of its RF environment. In the context of cognitive radio, this sensing typically takes the form of identifying whether spectrum is occupied by another link's transmission. An opportunity is the momentary vacancy of this spectrum that cognitive radio are supposed to be capable of exploiting. To this end, reconfigurable antennas offer two possible improvements of conventional antenna systems. Sensing with different antenna pattern configurations independent samples of the RF environment which can improve statistically reduce misidentification of spectrum opportunities, and improve the ROC of developed spectrum sensing strategies [**?**]. The use of reconfigurable antennas in spatially uncorrelated channels also offers the possibility of identifying spectrum opportunities that are available under some pattern configurations that are not available in others. This effectively increases the search space for opportunities which can lead to higher occurence of opportunity identification and improve cognitive throughput.

Cognitive radios must also determine an access strategy that will optimize the probability of a successful transmission given spectrum sensing information [**?**]. Intuitively, it is obvious that improving the fidelity of spectrum sensing information as discussed, would improve the efficacy of the designed access policy. There is added value in using reconfigurable antennas to improve the condition of already scarce spectrum opportunities. In this way throughput can be optimized by antenna reconfiguration by selecting opportunities in space time and frequency that have the best quality for transmission and have the least adverse impact on the wireless network in which they are transmitting.

V. CONCLUSION

The development of reconfigurable antenna technology has created a need for testbed environments that allow for the evaluation of their use in practical communication systems. The provided testbed offers the capability to not only evaluate the use of reconfigurable antennas in real-world environments, but also to develop and optimize the control framework that drives these antennas. The SDR framework provided offers a flexible platform for cross-layer communications design.

The research presented has shown the promise in using reconfigurable antennas in existing wireless technologies. The paradigm of cognitive radio has also been proposed as a means of improving spectral efficiency. This paradigm puts a premium on radio reconfigurability, making the incorporation of reconfigurable antennas an attractive area of research. Limited research has been done to consider the cross-layer design of cognitive radio algorithms that incorporate radio reconfigurability. Cognitive radio has a similar challenge of lacking an experimental environment for evaluating algorithm development in real world environments. For all these reasons, the Cognitive Antenna Testbed provides an ideal framework for the development of reconfigurable antenna cognitive radio designs.

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