Demo: Enhancing Indoor Spatial Reuse through Adaptive Antenna Beamsteering

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ABSTRACT

Widespread deployment of indoor wireless LANs has brought about many advantages, but at the same time posed tremendous challenges for interference management and service scalability. One means to improve wireless capacity in dense deployments is through simultaneous directional transmissions and receptions, but there has yet to be a coordinated approach that can adapt well to fast-changing channel conditions. In this demonstration we present a distributed directional antenna system to enhance spatial reuse in indoor scenarios. Our system is a holistic approach combining smart antennas, synchronous channel access, and an adaptive antenna beamsteering mechanism. We implement this system on software-defined radios and demonstrate the feasibility of dense spatial packing to maximize the network sum rate.

CCS Concepts

• **Networks → Cross-layer protocols; Network experimentation; Mobile networks;**

Keywords

Cognitive radios; smart antennas; spectrum sharing; spatial reuse; software-defined radios

1. INTRODUCTION

With the growing density and ubiquitous deployment of wireless networks, interference management becomes a critical problem for indoor wireless local area networks (WLANs). Unfortunately, the prevalent method of interference avoidance in WLANs—the 802.11 distributed coordination function (DCF)—scales poorly to maintain acceptable Quality of Service (QoS) and meet growing wireless capacity demands as the number of network nodes increases [4]. Consequently, significant effort has been made to improve spatial reuse in indoor environments, i.e. increasing the number of successful concurrent transmissions in a given channel and coverage area. In this work, we propose to tackle the interference problem and increase spatial reuse in indoor WLANs through synchronous directional transmissions with smart antennas. Specifically, we develop a distributed directional antenna system that comprises of: *(i)* compact, pattern-reconfigurable antennas that can be electronically steered to maximize signal power in certain directions, *(ii)* a time slotted medium access control (MAC) protocol where multiple links can be scheduled for concurrent directional channel access on millisecond granularity, and *(iii)* a distributed antenna orientation algorithm based on machine learning to maximize the individual goodput of each link.

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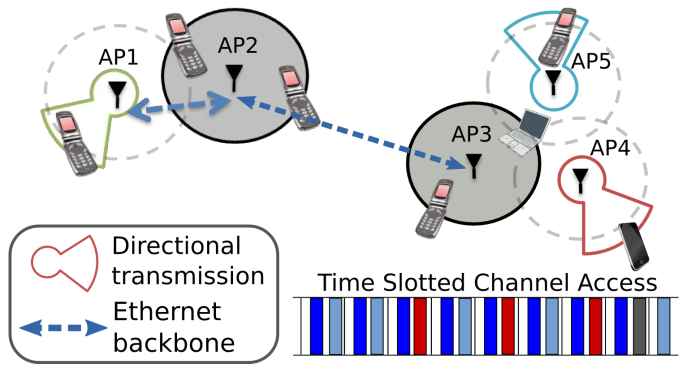

Figure 1: System architecture of the demonstrated distributed directional antenna system with high spatial reuse

The idea of improving spatial reuse using directional transmissions is not new; it has been applied extensively in outdoor settings through mechanisms such as cell sectoring in cellular networks and directional MAC [2] in wireless ad hoc networks. The indoor application scenario, however, is distinctly more challenging. Due to the rich-scattering environment and chaotic node locations, the multipath channel and interference conditions become unpredictable and more varied, leading to severe performance loss for unmanaged directional transmissions. Several directional MAC protocols have been proposed for indoor deployment, including DIRC and Speed [3]. These schemes rely on periodic received signal strength (RSS) measurements across all antenna orientations at both access points (APs) and clients to generate conflict graphs and schedule directional transmissions. In a fast-changing environment with client mobility and frequent handoffs, the cost of exhaustive RSS measurements becomes prohibitive. In contrast, our system assumes multiple directional AP-client links can always be spatially packed and relies on machine learning techniques to orient the antenna beams (see Sec. 2.2 for more details). Block acknowledgements are used to obtain steering outcomes and detect the corner cases where an optimal antenna configuration cannot be found. The APs coordinate with each other over an Ethernet backbone to exchange learning statistics and avoid potential oscillation in finding an equilibrium for network-wide antenna configuration. The system architecture is depicted in Fig. 1.

We implement the proposed system on WARP-TDMAC [6], our synchronous directional antenna testbed built on top of the Wireless open-Access Research Platform (WARP) [1]. We demonstrate the potential network sum-rate gains of our distributed directional antenna system over omnidirectional transmissions in a two-link interference scenario where both links are purposely scheduled to interfere in every data time slot.

2. SYSTEM IMPLEMENTATION

Our directional antenna system implementation consists of two primary components:

2.1 WARP-TDMAC Testbed

WARP-TDMAC integrates pattern-reconfigurable antennas into WARP 802.11-compliant physical layer and implements a time division multiple access (TDMA)-style MAC protocol to provide timing, synchronization, link scheduling, and programmable directionality to all radio nodes. Reconfigurable antennas provide inherent space and cost benefits by integrating many switchable radiating elements on a single device, thereby enabling steerable directed beams with a smaller number of RF chains and lower processing overhead than phased array and adaptive antenna systems. Our reconfigurable Alford-loop antennas [7] can radiate in both an omnidirectional pattern as well as four directed beams at 90° separation with controllable beam widths. Our software framework includes the antenna controller, PHY hardware abstraction layer, custom TDMA-based MAC, and upper layer functionalities. To the best of our knowledge, this is the first experimental testbed to offer real-time scheduling in both time slotted channel access and antenna orientation at the millisecond level. Details about the WARP-TDMAC testbed can be found in [6].

2.2 Antenna Orientation Algorithm

To increase spatial packing efficiency and avoid interference, each individual AP-client link employs an antenna orientation algorithm to autonomously steer the nodes' antenna beams in a way that maximizes the link goodput. We formulate the antenna orientation process as a non-stationary multi-armed bandit problem and apply the *adaptive pursuit* method [8] from reinforcement learning to solve it. As an example, consider what happens at the beginning of a downlink time slot for a particular AP-client link: the AP is presented with M possible antenna states (orientations) for transmission, and the client has N antenna states for reception. After making a Tx and Rx orientation choice in time slot t, the AP-client link receives a numerical reward $R(t)$, which we select to be the (downlink) packet delivery ratio (PDR), depending on the selected antenna states. The goal of the link is to orient its constituent nodes' antennas in each time slot so that the expected cumulative reward is maximized at the end of the run.

The adaptive pursuit strategy is a probabilistic selection policy; it identifies at each time step the reward-maximizing *selection probability distribution* over all antenna state combinations, and then proceeds to select the antenna states randomly according to that distribution. Adaptive pursuit has been shown to be well-suited for non-stationary environments, in which the reward generating processes associated with the antenna orientations do not remain the same over time. Furthermore, it can be fine-tuned to produce near-optimal results. Initial experimental results show that our distributed directional antenna system is highly resilient to both deliberate and unintentional co-channel interference, maintaining at a minimum 60% PDRs for all network links under varying degrees of interference.

3. DEMONSTRATION

We demonstrate our distributed directional antenna system in a real-time setting with two interfering WiFi links. All WARP nodes are equipped with reconfigurable antennas and communicate in the low-traffic WiFi channel 14 at 2.484 GHz. We employ an augmented reality mobile app called BeamViewer[1] [5], available on both iOS and Android app stores, to enable the audience to visualize and control the directional links on the fly. Link goodputs will be plotted on a monitor screen and in the mobile app at all times to observe the network throughput gains provided by our directional antenna system over omnidirectional transmissions.

4. ACKNOWLEDGMENTS

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[1] Demo video available at `http://beamviewer.io`

APPENDIX

A. DEMO REQUIREMENTS

- Four (4) WARP nodes equipped with reconfigurable antennas, and two laptops (provided by us)
- Two (2) 6-foot tables arranged in parallel and facing each other, with a separation distance of about 6-7 feet
- One large (at least 24-inch, preferably rollable) monitor display, with VGA cable
- Two (2) poster stands
- Both wired (for the laptops) and wireless (for mobile devices) Internet access
- One hour demo setup time