Integrated Beam Steering and Scheduling for Spatial Reuse

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***Abstract*—Increasing spatial reuse of spectrum is fundamental to improving the capacity and usefulness of large wireless networks. Steerable and adaptive antennas facilitate reuse, and a number of MAC-layer protocols have been developed for them. Existing protocols, however, do not allow the MAC (or scheduling) process to fully consider the capabilities of antenna reconfiguration, or vice-versa. Without such integration between MAC scheduling and physical antenna configuration, a "chicken-and-egg" problem exists: If antenna decisions are made before scheduling, they cannot be optimized for the communication that will actually occur. If the scheduling decisions are made first, the scheduler cannot know what the actual interference and signal strength properties of the network will be.**

To take full advantage of the dynamic capabilities of an advanced antenna system, MAC-layer processes need to know about not just any particular RF-level configuration, but about the range of *possible* configurations. This research has two goals: To produce a fully-integrated algorithm for STDMA scheduling and beam steering, and to *systematically* evaluate the costs and benefits of different approaches to such integration.

Our approach to this research is based on a combination of mathematical analysis, simulation, implementation and deployment, and empirical measurement.

I. RESEARCH OBJECTIVES

We evaluate the potential gains from a tighter integration between MAC-layer scheduling and advanced antenna system configuration. There is substantial existing research on MAC layers for smart antennas, but none of it gives significant attention how the MAC and antenna configuration systems interact. When the MAC-layer decision process takes the antenna configuration as given, it is unable identify situations in which a different antenna configuration would create better options at the MAC layer. Conversely, if the MAC layer assumes that a given set of concurrent transmissions can be accommodated by physical-layer antenna reconfiguration, it runs the risk of creating a high-interference situation in which none of the links function well. That risk can be mitigated by conservative assumptions, but that means passing up legitimate opportunities for spatial re-use.

This research is focused specifically on spatial-reuse TDMA, both because it has promising performance in its own right, and because an *explicit* scheduling process is easier to evaluate and improve than the emergent scheduling behavior of a contention-based MAC. STDMA tends to perform better than CSMA in terms of spatial re-use, and STDMA with smart antennas performs better than with omni-directional ones [1]. Even so, it is easy to construct artificial scenarios in which the best current smart-antenna STDMA algorithms achieve less than half the performance of an integrated algorithm. It remains to be seen how significant the gains from integration will be in "naturally-occurring" scenarios, but that is one of the questions being addressed.

We are developing and evaluating specific integrated algorithms for beam selection and scheduling, and on systematically evaluating the costs and benefits of such integration in general. It is expected that this research will provide both useful prototype systems and general guidance for using smart antennas in dense wireless networks.

II. METHODOLOGY

To be truly useful, this research needs to be both theoretically rigorous and firmly grounded in reality. Consequently, we are pursuing both "top-down" analytical and "bottom-up" measurement approaches to this problem. The analytical modeling is necessary because the state-space is too large and the interactions too complicated to have confidence in an intuitive understanding of the problem. Conversely, measurement and deployment are necessary because analytical models so frequently fail to capture the true complexity of radio systems, and a valid analysis based on faulty assumptions is of limited usefulness.

A. Analytical Model

As a starting point, the combination of beam steering and scheduling are being considered as a single optimization problem. It is impractical to solve directly, but provides a conceptual basis for implementable solutions. There have been several approaches to optimization-based scheduling, and my work follows the formulation in [2]. The objective is to find the shortest-duration schedule which satisfies relative throughput constraints and also constraints representing limitations of the underlying technology and physical environment. Pure STDMA scheduling, as approached in [2] or [3], is a very large mixed integer (linear) program (MIP). Both papers break the problem down according to *Dantzig-Wolfe decomposition* and use delayed column generation (also referred to as implicit enumeration) to evaluate only a necessary subset of the state space.

Adding antenna configuration to the optimization problem makes it a mixed-integer non-linear program (MINLP) of polynomial degree 3, as well as exponentially increasing the size of the decision space. To address this complexity, we introduce several additional decompositions so that the hardest problem which needs to be solved directly is a linearly-constrained mixed-integer quadratic program (MIQP) with a very small number of non-zeros. The core underlying model is Lagrangian relaxation to separate link scheduling and antenna configuration into separate decomposed relaxed primal problems. A solver based on this decomposition has been implemented using the BCP framework from COIN-OR [4]. This produces a *provably optimal* solution to joint scheduling and beam steering, which is useful both in its own right and as a reference point for evaluating simpler and faster algorithms.

The problem decomposition provides conceptual insight which has value beyond any specific solver: It provides a way of separating the main problem into manageable subproblems, while maintaining a rigorous understanding of their combined behavior [5]. The decomposition of the joint scheduling and beam steering problem introduces a coupling variable which can be interpreted as a signal-strength price or value.

This coupling effectively enables a scheduling process to express not just what it has chosen, but what it would like from the physical layer in order to be able to choose something better.

B. Measurement Studies

It is easy to develop an interesting formalization, only to find that poor assumptions weaken its usefulness. This program of research aims to avoid this as much as possible, through both fundamental measurement studies and system implementation and testing.

This work has produced two significant pieces of research infrastructure so far: 1) A wide-area outdoor testbed for experimenting with steerable antennas in wireless networking [6]. This includes a generalized STDMA MAC framework which will be used for system testing, as well as infrastructure for more general measurements. 2) An empirically-based model of the interaction between antenna directionality and environmental effects [7]. Existing simulators, as well as widely-used analytical models, incorporate a very naïve understanding of the relationship between the antenna and the actual distribution of signal strength. Our measurements have produced models which better describe and quantify the behavior observed in real environments, and validated simulation methods which incorporate these models [8].

Simulation has neither the clarity of mathematical analysis nor the reality of actual implementation, but it is a necessary evil. Simulated experiments will be used to explore system behavior at scales which are too large to implement on our testbed, and to examine the effects of parameter interactions when the number of combinations to be considered are too many for practical direct implementation. When simulation is necessary, the results of our real-world studies will be used to improve the realism.

C. Implementation

In the final stage of this work, several integrated scheduling and beam steering algorithms will be implemented on the testbed described above. This serves several purposes. Foremost, it provides a ground-truth validation of the ideas and models proposed. Additionally, it enables evaluation of the many systems issues which are not part of the analytical models at all. These include:

- Estimation of the channel conditions and demand in a “live” system when they are not given *a priori*.
- Dynamic behavior of the algorithms (and system as a whole) when the set of nodes, channel conditions, or demand change over time.
- Computational and communication overhead of the algorithms.

We have built a software and hardware foundation for implementing and evaluating a joint STDMA and beam steering system. This includes the testbed itself and a number of *Linux* kernel driver modifications, several of which have been released for public use [9].

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