Optimal Scheduling and Antenna Configuration

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Abstract—**My dissertation examines algorithms for optimal spatial reuse TDMA scheduling with reconfigurable directional antennas. I present and solve the joint beam steering and scheduling problem for spatial reuse TDMA and describe a prototype implemented system based on the algorithms developed.**

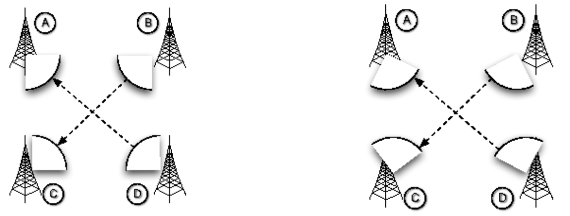
The current prototype achieves up to a 600% speedup over TDMA with a mean of 234% in the experiments to date. I use an optimization decomposition approach to arrive at a working distributed protocol which is provably equivalent to the original problem statement while also producing optimal solutions in an amount of time that is *at worst* linear in the size of the input. This is, to the best of my knowledge, the first actually implemented wireless scheduling system based on dual decomposition.

Scheduling for spatial reuse (whether explicit or implicit) is fundamental to the efficient use of finite radio spectrum across a wide range of communication systems.

I. INTRODUCTION

My dissertation investigates a novel approach to minimizing interference and maximizing spatial reuse for competing spectrum users. These concerns are significant any time interference is a limiting factor, including packet radio networking (using base stations or multi-hop meshes), mobile telephony, and radio repeaters. This work is oriented toward explicitly scheduled Medium Access Control (MAC) protocols such as Time Division Multiple Access (TDMA).

I present a joint optimization process for integrating scheduling and beam steering to achieve greater spatial reuse than is given by solving the two problems separately. Without such coupling between the MAC scheduling and physical antenna configuration processes, 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, on the other hand, the scheduling decisions are made first, the scheduler cannot know what the actual interference and communications properties of the network will be.



(a) Nodes have their beam pattern main lobes pointed directly at their communicating partner.

(b) Scheduling-aware antenna configuration: Beam patterns chosen *to enable* a denser schedule.

Fig. 1: Example: Links BC and DA can be scheduled together, with the right antenna configurations.

Figure 1 illustrates the potential pitfalls of treating scheduling and antenna configuration separately. The best case (b) can occur only if the antenna patterns and schedule are chosen jointly – the schedule is impossible with a naïve antenna choice (a), and there’s no reason for the better antenna patterns to be chosen unless that schedule is being considered.

This dissertation is the first work to deeply consider the integration of optimal scheduling and antenna configuration. Several prior works have considered some combination of the two, but as completely separate processes with the potential limitation just described (*e.g.* [1], [2]) or relied on simplifying assumptions about what effects antennas would have (*e.g.* [3], [4].) An efficient, but not necessarily optimal, centralized system is described in [5]. The “optimal” solution is often not the best one: The formal representation never captures every relevant aspect of a system, and the incremental cost of going from “pretty good” to optimal may be significant. Much of the value in finding an optimal solution is that it gives a reference point for evaluating approximate solutions. Additionally, finding an optimal solution frequently yields insights into the problem structure which are useful even when optimality is not required.

In addition to addressing joint scheduling and beam steering, this work seeks to explore optimal scheduling more generally. Optimization decomposition has been suggested as an organizing principle system architecture [6], and there is a body of theoretical work on dual-decomposition in scheduling [7], [8], but this is the first implementation of decomposition-based scheduling.

The remainder of this extended abstract will summarize the mathematical formulations identified, the design of a prototype implementation, and the research remaining to be done.

II. PROBLEM FORMULATION

This dissertation introduces a joint optimization formulation for spatial-reuse TDMA (STDMA) scheduling and antenna configuration, the Joint Beam Steering and Scheduling Master Problem (JBSS-MP) described below. It takes as a starting point the STDMA formulation of [9] and extends it to consider antenna choices having arbitrary effects on each node’s gain toward all others.

A. Joint Beam Steering and Scheduling Master Problem

Our model of the problem is as follows: An STDMA schedule consists of a repeating cycle of frames, where each frame is sub-divided into discrete slots. Within each slot, one or more links may be activated. Traffic load is given at the link level, as the number of slots (per frame) which any given link needs.

The objective is to minimize the total slots per frame. The variables are which sets of links to activate concurrently, how to configure each node's antenna in each such set, and how many slots to assign to each set. The major interesting constraints are:

1) Every link must be active in sets having a combined number of assigned slots greater than its demand.
2) In each set, any node can be part of at most one link.
3) For every *active* link, the signal to interference and noise ratio (SINR) must exceed some threshold. This constraint includes as free variables the antenna gains at each active node.
4) Every node must choose one antenna configuration.[1]
5) The antenna gains used in computing the SINR in constraint 3 must correspond to the antenna patterns chosen. Arbitrary (measured) antenna and path effects can appear in this constraint.

The JBSS-MP formulation includes a particular set of assumptions, among them: Demand is given at the link (not path) level; loads reflect proportional allocation of bandwidth, not absolute rates; interference is additive; and SINR requirements are discrete thresholds. Some variations are trivially accommodated: Multiple modulation schemes with different rates and SINR thresholds, and variable transmit power, require essentially no change to the formulation or its decomposition. Different utility functions, so long as they depend only on the time allocated to each link (or link-rate tuple), change the formulation but not the decomposition. On the other hand, changes to the interference model are more fundamental.

The JBSS-MP program captures the system goals and requirements, but is computationally intractable. The objective function is defined over the set of all possible subsets of links, which is exponentially large, the SINR constraint is a polynomial of degree 3, and many of the variables are discrete. Optimal scheduling is fundamentally NP-hard [10], but we can exploit the problem structure to do much better than a naïve MINLP problem.

B. Optimization Decomposition

The bulk of my dissertation research is devoted to transforming the JBSS-MP problem, which is correct but difficult to solve, into a set of equivalent formulations which admit efficient solutions. The ultimate result is that the single large and ill-structured problem is replaced by many iterations over several simpler small problems, which can be implemented in a distributed way.

The first step is to use *Dantzig-Wolfe decomposition* [11] to split JBSS-MP into a Restricted Master Problem (RMP) and the Configuration and Link Activation Problem (CLAP). After working through two intermediate forms, CLAP is decomposed into the Fixed-link Antenna Reconfiguration Program (FARP), and the Relaxed Primal Fixed-antenna Link Activation Problem (RP-FLAP). FARP and RP-FLAP are separable, and are split into distributed, per-node versions, the Single Node Antenna Reconfiguration Problem (SNARP) and Single Node Relaxed Primal FLAP (SNRP-FLAP). Lastly, we transform SNRP-FLAP to reduce oscillations, producing what we call the Single-node Dual Quadratic FLAP (SDQ-FLAP). These transformations are shown schematically in fig. 2.

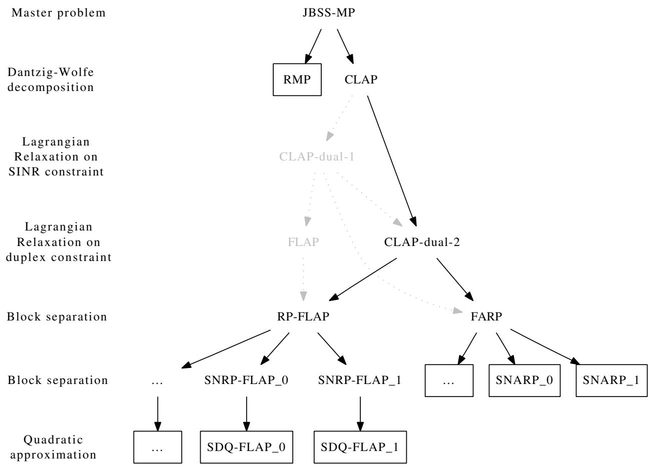


Fig. 2: Tree of decompositions / reformulations

Without going into the resulting subproblems in detail, the general structure is this: The restricted master problem (RMP) takes as inputs a set of feasible concurrent link sets and allocates time to each set to satisfy the link load demands in the minimum total time. In doing so it finds dual prices for the demand constraints, which are inputs to the remaining subproblems. For every node in the network i, there are two Lagrangian relaxed primal subproblems, the Single Node Antenna Reconfiguration Problem (SNARP) and the Single Dual Quadratic Fixed-antenna Link Activation Problem (SDQ-FLAP), which compute the antenna state and link use, respectively. These subproblems take as input the demand constraint prices from RMP and estimated Lagrange multipliers (effectively prices) for half-duplex and minimum SINR constraints. The Lagrange multipliers and estimated primal values are updated by iterating between the subproblems and subgradient steps. Primal feasible results from this subgradient method are fed back into the RMP as new concurrent link sets.

C. Multiple Objectives

In the course of building a system based on this formulation, we found something initially confusing, but obvious in retrospect: Because SINR requirements are thresholds, the program has no reason to find the "best" antenna patterns, only ones good enough to support the best schedule. Intuitively, we want both the shortest schedule possible *and* the highest SINR possible. Unless they are orthogonal (which these are not) one cannot in general have the optimal value of both objectives at once. We take a strictly hierarchical approach and find the optimal schedule as our primary objective, and then try to improve SINR subject to the constraint that the optimal schedule must remain feasible.

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[1] Strictly, each node must choose a convex combination of antenna patterns, but this is ultimately an equivalent requirement.

III. SYSTEM

A. Design

This mathematical approach is realized as a set of processes implementing a distributed asynchronous optimization scheme after [12]. Every node is continuously running its own subproblems and incremental subgradient steps and sharing the results; estimates received from other nodes are combined with local estimates based on weighted averaging rules. To prevent this control traffic from completely overwhelming the channel, we implement a sender-side buffering and caching scheme which (a) aggregates messages and only transmits when it has a full packet or a staleness requirement is met and (b) only transmits the *last* value when a variable is updated repeatedly during buffering. After buffering, metadata messages are sent as broadcasts. There is an additional termination / RMP process which monitors the messages to see if convergence or early termination conditions are met, and invokes the RMP if so. Our prototype runs on an outdoor testbed of embedded Linux computers with phase array antennas and 802.11g wireless interfaces [13], running a custom-developed STDMA MAC [14].

B. Prototype Limitations

The prototype is efficient *algorithmically*, but not as a system. Processing is implemented in user space using Python scripts, with AMPL and CPLEX or IPOPT processes being spawned at every iteration to solve problems which turn out to be reducible to simple arithmetic. Moreover, much of this is done on a *remote host* because said software is not available for the ARM architecture. Consequently, the ratio of elapsed time to user CPU time is consistently > 1000. Similarly, the design of our driver combined with Linux kernel version compatibility issues makes time slots shorter than ≈ 30 ms impractical, leading to (data + control traffic) frame lengths of ≈ 1 s, when a cycle time of $10 - 100$ ms would suffice.

C. Challenges

Radio propagation is a complex phenomenon, and *a priori* estimates are frequently wrong. The difficulty of modeling directional antenna effects specifically is addressed in [15]. Consequently, this system and formulation were designed to accept arbitrary measured values for path loss and antenna effects as inputs. The current design treats this as an off-line process, conducting batches of active measurements taking $O(np^2)$ time for n nodes with p antenna states each. Making measurements in a way that gives good and *current* estimates without undue overhead is a difficult and largely open problem.

IV. REMAINING WORK

As it stands, my dissertation contains significant mathematical and algorithmic analysis, but only a little empirical system evaluation. The main remaining tasks are (a) to compare the quality of schedules produced by my approach with those from approaches such as [2] and [5], (b) to address the system inefficiencies discussed above, and (c) to empirically compare this scheme with other operational MAC protocols.

In testbed experiments, the described system succeeds in finding and scheduling link combinations which are not possible without integrated scheduling and beam selection. Measurements show that avoidable mutual exclusion of type shown in fig. 1 on page 1 affects 20-40% of link pairs, which suggest a significant potential gain, but direct comparisons remain to be done.

V. CONCLUSIONS

My results to date support decomposition-based optimal scheduling as a theoretically rigorous *and practical* approach to managing the complexity of wireless networks. Antenna effects are less predictable and more mathematically awkward than other physical-layer adaptations such as power control, modulation (rate) selection, and channel selection, so success in this domain strongly suggests the viability of similar approaches to the others, or their combination.

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