Efficiency of Wireless Networks: Approximation Algorithms for the Physical Interference Model

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Efficiency of Wireless Networks: Approximation Algorithms for the Physical Interference Model

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Abstract

In this monograph we survey results from a newly emerging line of research that targets algorithm analysis in the physical interference model. In the main part of our monograph we focus on wireless scheduling: given a set of communication requests, arbitrarily distributed in space, how can these requests be scheduled efficiently? We study the difficulty of this problem and we examine algorithms for wireless scheduling with provable performance guarantees. Moreover, we present a few results for related problems and give additional context.

Contents

1

Introduction

Despite the omnipresence of wireless networks, their fundamental communication limits are not fully understood: designing and operating a wireless network is often a matter of trial-and-error, regardless of whether it is a Wireless LAN in an office building, a GSM phone network, or a sensor network on a volcano.

We are interested in the fundamental communication limits of wireless networks. Given an *arbitrary* wireless network, and an *arbitrary* traffic pattern, we want to utilize the full bandwidth of our network. One of the most challenging characteristics of wireless networks is the fact that mutual interference impairs the quality of signals received and might even prevent the correct reception of messages. Efficient algorithms that coordinate the transmissions are therefore essential for the operation of wireless networks. To this end, we want to understand the maximum possible spatial reuse, i.e., which devices can transmit concurrently, without interfering. Given a set of communication requests, what is the minimum time needed to schedule all these requests successfully? How should media access be organized in a given network? In an existing wireless network, is it sensible to add relays, and where are they to be placed?

Evidently, if one hopes for analytic answers to questions like these, one must first decide for a reasonable wireless transmission model. In the past, a large fraction of analytic research on wireless networks has focused on models where the network is represented by a graph. The wireless devices are mapped to nodes and any two nodes within communication (or interference) range are connected by an (annotated) edge. Such graph-based models are particularly popular among higher-layer protocol designers, hence they are also known as *protocol models*. Unfortunately, protocol models are often too simplistic: consider, for instance, a case of three wireless communication pairs, every two of which can be transmitting concurrently without a conflict. In a protocol model, one will conclude that all three transmissions may transmit concurrently as well, while in reality this might not be the case since wireless signals accumulate. Instead, it may be that any two transmissions together generate too much interference, hindering the third receiver from correctly receiving the signal of its sender. This many-to-many relationship makes understanding wireless transmissions difficult; a model where interference accumulates seems paramount to truly comprehending wireless communication. Similarly, protocol models oversimplify wireless attenuation. In protocol models the signal is usually "binary", as if there was an invisible wall at which the signal ends abruptly. Not surprisingly, in reality the signal strength decreases gracefully with distance. Because of these shortcomings, results for protocol models are often not applicable in reality.

In contrast to the algorithmic ("computer science") community which focuses on protocol models, researchers in information, communication, and network theory ("electrical engineering") are working with wireless models where interference accumulates and attenuation is taken into account. A standard model is the physical model; we will formally introduce it in Section 2. In this model, the energy of a signal fades with the distance to the power of the path-loss parameter α. If the signal strength received by a device divided by the strength of interference caused by concurrent transmitters (plus the noise) is above some threshold β (signal-to-interference-plus-noise ratio (SINR)), the receiver can decode the message, otherwise it cannot.

Unfortunately, most work using the physical model does not provide algorithms with provable performance guarantees. Usually heuristics are proposed instead, evaluated by simulation. Analytical work is done for special cases only, e.g., networks with a grid structure, or random traffic. However, these special cases do not give much insight into the complexity of the problem; also, it seems difficult to derive new protocols from analytical work on special cases. If one is interested in the capacity of an *arbitrary* wireless network, and how this capacity can be achieved, an algorithmic approach seems unavoidable.

In this monograph we present recent results that combine the best of both worlds: we present algorithms and bounds for arbitrary wireless networks (*not* random node distributions), using the physical model (*not* the protocol model). We believe that bridging the gap between protocol designers and communication theorists is a fundamental challenge of the coming years, a hot topic for the wireless network community with implications for both theory and practice. To the best of our knowledge, research in this emerging area is only a few years old [66]. Nevertheless, the body of work is growing rapidly. Hence we cannot provide a complete survey; instead we focus on wireless scheduling using a simple physical model. More precisely, given a set of communication requests, arbitrarily distributed in space, how can these requests be scheduled efficiently? This question may be formulated in several ways, using different parameters. One might want to know the maximum number of requests that can be scheduled simultaneously. Alternatively, one might ask what is the minimum time needed to schedule all requests. Essentially, the main objective is to achieve efficient spatial reuse, considering wireless interference among nodes transmitting concurrently. Such results promise to lead to answers to questions such as “What is the throughput capacity of a specific wireless network?”, and “*How* can this capacity be realized?”

This monograph is organized as follows: In Section 2 we formally define the models and problems of interest; in addition we present a robustness result that shows that small perturbations in the model do not fundamentally change the results. The main content is in Sections 3 and 4. In Section 3 we study wireless scheduling *without* power control, and in Section 4 *with* power control. As we will see, most of the questions are NP-hard, so we settle for so-called approximation algorithms, algorithms that guarantee that a solution is at most a bounded factor worse than optimum. We focus on simple (and to some degree teachable) results, and usually merely mention more elaborate techniques. In Section 5 we will survey a few results beyond scheduling. Finally, in Section 6 we provide additional context about related areas.

At the time of writing, results are emerging that reconsider problems and results for protocol models successfully in the physical models. Indeed, this direction of research is increasingly popular, as first surveys and overview articles [62] are published. Analogously, we hope that some of the ground-breaking research on special-case topologies in the physical model may be generalized and studied in an algorithmic way.

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