Scheduling in Wireless Networks

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Abstract

We present a review of the problem of scheduled channel access in wireless networks with emphasis on ad hoc and sensor networks as opposed to WiFi, cellular, and infrastructure-based networks. After a brief introduction and problem definition, we examine in detail specific instances of the scheduling problem. These instances differ from each other in a number of ways, including the detailed network model and the objective function or performance criteria. They all share the "layerless" viewpoint that connects the access problem with the physical layer and, occasionally, with the routing layer. This review is intended to provide a reference point for the rich set of problems that arise in the allocation of resources in modern and future networks.

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1

Introduction

This volume examines in some depth the fundamentals of the problem of scheduling transmissions over a multi-user shared channel. The origins of this problem are found in the area of Multiple Access (MA) [4, 35], where the traditional concept of simple "orthogonal" time-division [20] was enriched through the ideas of random access (known, more colloquially, as ALOHA [1, 32, 55]).

The original question was how to ensure the most productive use of the channel (that is, maximize the total, or "sum" throughput) when users have sporadic, "bursty", need to transmit and cannot coordinate their needs and actions amongst them. At the same time, the issue of sharing a channel was examined at a deeply theoretical level through an information-theoretic approach that aimed at determining the best "joint" rates at which different users can transmit over the shared channel if they can design their codebooks jointly and transmit without further coordination at the "protocol" level, that is without worrying about when to transmit. The reason for the latter, and very important, difference was that in the information-theoretic approach the sources were not assumed to have "bursty" and sporadic need for the channel but were backlogged and simply needed to transmit all the time. Of course, in that case, the receiver was assumed to be equipped with a multi-user detector (a concept that was formalized much later through the work of [71]) that was able to decode successfully the simultaneous transmissions of all users.

The first approach, which has been more characteristic of the work by what we call the "networking" community, has led to a large variety of protocols and standards that try to achieve the goal of maximum use of the channel through elaborate variations of practical exploitation of possibilities, such as feedback, carrier sensing, storing unsuccessful packets, often even relaying, etc. A large volume of literature exists that documents the efforts in this direction, e.g., [24, 42, 45, 56, 58, 59, 61, 66, 67, 68] to sample a few. The second approach has seen a similar voluminous body of work that has been mostly preoccupied with determination of the Shannon capacity region in variations of the shared channel model, such as pure multi-access, pure broadcast, relay, and interference models (see e.g., [21, 22, 27, 41, 62, 72]).

In both cases, the two approaches have fallen short of their ultimate goal due to the fundamentally complex nature of the problem. In the first case the major difficulty arises from the "dimensionality" issue, that is, the combinatorial nature of the problem, as the number of users increases. In the second case, the difficulty lies in the tremendous increase in analytical intractability of the Shannon-theoretic approach as the channel model becomes more complicated and/or the number of users increases.

The scheduling problem becomes more interesting and relevant to practice when the two approaches are partially blended. In particular, the first approach requires that transmissions from more than a single user cannot co-exist successfully in the same time slot. However, with multi-user detectors and by adjusting the transmission powers and the bit rates it is possible for several users to be successful simultaneously. Thus the question is what subset of users should be activated in each time slot of a frame. It must, of course, be taken into account that when more users are squeezed into the same slot their individual transmission rates must be reduced in order for them to tolerate each-others interference (and/or their transmission powers must be accordingly adjusted). Since the objective is to maximize bit/sec rates rather than the, not so informative, packets/slot rates, a clear trade-off emerges. Is it preferable for more users to transmit simultaneously but at reduced individual rates or is it better to time-share access by smaller sets of users that transmit, however, at higher individual rates? The answer is not clear and it depends on the specific environment, performance criterion, channel quality and gains, detector structure, modulation scheme, error control coding, etc.

In this volume, we follow this intermediate approach, more in the line of what the community has been referring to as "cross-layer" or "layerless" approach ([36, 40, 57, 63, 69]). Cross-layer approaches try to exploit linkages between the OSI layers, while layerless approaches consider, instead, the determination of variables of different layers simultaneously. In this volume we adopt the basic networking view of scheduling packet transmissions but, at the same time take into consideration the bit-rates that correspond to multi-user reception capability through physical-layer models. The purpose of this volume is to present a few samples of prior literature on the problem of scheduling and then outline through detailed illustrations some specific results that we have recently developed in addressing the problem in an innovative way. It is by no means exhaustive. The main two overarching ideas in our approach have been (i) to include physical-layer criteria in the determination of the probability of successful transmission and (ii) to opt for reducing the search space, rather than developing heuristics, in the case of combinatorial optimization problems. That is, in the "erasure" channel model (e.g., [19, 60, 70]), which has been gaining increasing attention recently and in which the probability of packet success is provided through a parameter value, we express this parameter value in terms of power, transmission bit-rate, and other variables from traditional physical layer communication-theoretic analyses. Furthermore, in the case of protocol of access optimization problems that are purely of integer programming nature, we do not follow the alternative of inventing heuristic sub-optimal solutions but, rather, we insist on rigorous optimization within the confines of a set of reduced solution space. We believe that the latter approach reveals insights that intelligent heuristics often fail to provide.

The first formulation of the problem of scheduling for efficient access to a shared channel, that we are aware of, appeared in [18]. A simple collision channel model had been considered but with the possibility of spatial re-use. That is, an "interference map" was assumed in terms of a graph that described all the independent sets of nodes in the graph, namely those sets of nodes that do not include "adjacent" nodes. The objective was to determine the shortest length of a frame of slots that would allow all nodes to transmit once in the frame without violating the "interference" constraint imposed by the interference rules on the graph. It was shown that the problem is NP-complete, and a distributed heuristic was developed that showed decent performance compared to the optimum that was computable in "small" instances of the problem.

This problem was revisited in more generality through a continuous approximation of the structure of the frame schedule in [26] where each interference-free set of nodes could be activated for an arbitrary amount of time and, again, the objective was the determination of the shortest duration of a schedule that would accommodate a given demand. It was shown that the continuous version of the problem could be solved in polynomial time, but there was no characterization of the optimal solution. A variation of this problem formulation that incorporated some physical-layer attributes was studied in [10, 11, 12].

Subsequently there has been a great deal of variations of these formulations that have focused mostly on heuristics and approximation ratios. A totally new attack to the problem of scheduling was developed in [66] where, again for a graph-based model of constraint-node-sets (i.e., sets of nodes that can transmit successfully at the same time), the objective was to determine not a schedule anymore, but, rather, a scheduling rule for these constraint-sets that guaranteed that if the input load to the network could be accommodated without excessive delays, then that rule of activation would assure that the delay objective would be met. The solution to this problem, which is intimately related to the notion of stable throughput region in a network, and that was the subject of the inaugural issue of the Foundations and Trends in Networking series [23], came to be known as the *back-pressure* algorithm and it has received extensive attention over the years with generalizations that include physical layer effects. In fact, the last section in this volume includes a particular generalization of the back-pressure result that introduces the notion of uncertainty in the knowledge of the channel state [52].

In what follows we formulate a precise model for the sharing of a common channel and examine several different variations of the scheduling problem that include different optimization criteria (e.g., proportional fairness), a minimum-time draining of the network with an initial load, and an asymptotically optimal policy determination for a multicast version of the problem. Due to the combinatorial nature of the scheduling problem, we also discuss a method for reducing the scheduling complexity. Finally, the general version of the back-pressure algorithm with imperfect channel state information (as alluded above) is presented and discussed.

The detailed work in the following sections represents research performed by the authors that led to the Ph.D. dissertation of Dr. Pantelidou and several recent journal publications and conference presentations. It is presented here in the general context of channel access and in an integrated and unified way.

1.1 Network Model

We consider a wireless network of M, possibly mobile, nodes each of which is equipped with a single transceiver (transmitter and receiver). We denote by the set $\mathcal{M} = \{1,\dots,M\}$ the set of all nodes in the network. We also denote by $\mathcal{L} = \{1,\dots,L\}$ the set of all links that can be potentially established among the M network nodes. The number of such links, L, can be as large as $M \times (M-1)$. We consider a slotted-time model where without loss of generality each slot t takes integral values, i.e., $t \in \{0,1,\dots\}$. At time slot t, each network node $n \in \mathcal{M}$ transmits at a power level $P_n(t)$. We denote by $\mathbf{P}(t)$ the vector of transmission powers at every network node, i.e., $\mathbf{P}(t) = (P_n(t), \forall n \in \mathcal{M})$. We assume that the power of the thermal noise is common for every node in the network. This assumption is non-restrictive and is made merely to simplify notation. We denote the power of the thermal noise by the variable N_0. Our results are valid also when the thermal noise is different at the various network nodes. It is often taken to be the same at all nodes for simplicity since it is not important and this will be the assumption we also make throughout this volume. The process $\{\mathbf{G}(t)\}_{t=0}^{\infty}$ defines the channel conditions between every pair of nodes in the network and it is assumed to change only at the beginning of a time slot t. Specifically, at time slot t the channel state $\mathbf{G}(t) = \{G_{(n,m)}(t),\ n,m \in \mathcal{M}\}$ gives the channel conditions between every pair of nodes $n,m \in \mathcal{M}$. We assume that the channel follows a block fading model with block length equal to the duration of a time slot. Hence, we assume that the channel conditions are allowed to change *only* at the beginning of each time slot and remain constant throughout the slot duration. The channel effects in our model can be due to node mobility, fading, pure path loss, etc. We assume that the channel process takes values in a set $\mathcal{G}$.

In certain sections of this volume we will assume that the channel is time-invariant. This is not only to make the solution of the scheduling instances tractable, but also to illustrate how the scheduling decisions are affected by the underlying channel conditions. Furthermore, in the rest of the volume, except for Section 5, we will ignore routing and assume single-hop networks where the M network nodes are separated in a set of sources of traffic, $\mathcal{T}$, and a set of destinations of traffic, $\mathcal{D}$, such that $\mathcal{M} = \mathcal{T} \cup \mathcal{D}$ and $\mathcal{T} \cap \mathcal{D} = \emptyset$. The single-hop network assumption, albeit simplifying, is interesting and highly non-trivial since it captures the fundamental problems that arise due to interference, when multiple nodes attempt simultaneous channel access.

Depending on the optimization criterion, in the rest of this volume we will assume three different cases, namely (a) sources that are *saturated* and always have data to transmit whenever they are activated, (b) sources with a *finite* amount of data traffic, and (c) sources with *bursty* arrivals. We will also consider three different traffic types, namely *unicast* traffic that originates from a single source and is destined to a single destination, *multicast* traffic that originates from a single source and is destined to multiple destinations, and *anycast* traffic that originates from a single source and is destined to any node within the set of destinations.

1.2 A Criterion for Successful Transmission

The fact that the wireless medium is shared by the network nodes poses limitations on the set of nodes that can concurrently transmit successfully.

In this volume, we incorporate these constraints on medium access through the Signal to Interference plus Noise Ratio (SINR) criterion. This model is of course approximate since it models the interference as Gaussian noise. However, it is intuitive, reasonable, and increasingly accurate as the number of interferers increases. We will say that a link exists when the transmission powers of the network nodes are given by the power vector $\mathbf{P}(t) = (P_n(t), n \in \mathcal{M})$ and when a node n transmits to node m (or that the transmission from n to m is successful) if the ratio of the received signal power to the sum of the thermal noise and the total interference at m exceeds a certain threshold γ_m, i.e.,

$$\mathrm{SINR}^{\mathbf{P}(t)}_{(n,m)}(t) := \frac{P_n(t) G_{(n,m)}(t)}{N_0 + \sum_{n'=1, n' \neq n}^{M} P_{n'}(t) G_{(n',m)}(t)} \geq \gamma_m. \tag{1.1}$$

The exact value of the SINR threshold γ_m depends on various factors, such as the transmission rate, the target probability of bit error, the coding and modulation techniques employed at the transmission, etc. In this volume, we will only consider the dependence of this threshold on the transmission rate and assume that the rest of the parameters affecting it are fixed. It is well-known that the maximum transmission rate is an increasing function of the SINR threshold (see e.g., [25]). This gives rise to the following *trade-off*: By lowering the transmission rate, the corresponding value of the threshold decreases and hence more transmissions can jointly satisfy the condition of (1.1). On the other hand, by increasing the transmission rate the SINR threshold increases, thereby restricting the number of nodes that can concurrently access the channel successfully. Thus, it is not clear whether allowing more concurrent transmissions (less time-sharing) at lower rates is preferable to allowing fewer concurrent transmissions (more time-sharing) at higher rates. Shedding light in this trade-off will be one of the main objectives of this volume.

In this volume, we will consider this trade-off in a network where T sources of traffic wish to access the wireless medium. Under this setting, one extreme is to increase the threshold values so that only a single source can successfully transmit at any given time, that is, as in a Time Division Multiple Access (TDMA) fashion. Another extreme is to decrease the thresholds to the maximum values that allow all sources to successfully access the channel concurrently. In the latter case although more sources access the channel simultaneously, their rates will be significantly lower than the corresponding rates under TDMA operation. However, since they transmit continuously rather than in a TDMA fashion it is not clear how the long-term average rates of these two schemes compare to each other. These two extreme cases of operation will also be in the focus of this volume.

1.3 Organization of the Volume

The rest of the volume is organized as follows. In Section 2 we consider the minimum-length scheduling problem in single-hop wireless networks under unicast traffic. We present a rate control and scheduling policy that operates under the objective to empty a finite amount of traffic in the network queues in minimum time. We consider both the cases of static and time-varying networks. Next, in Section 3 we make a different assumption on the network traffic and performance criterion. In particular, we assume that the sources are sources of multicast traffic. Furthermore, we assume that they are saturated, that is, they always have data to send whenever they are activated. We obtain an on-line, gradient-based rate and power control algorithm that maximizes the overall network utility under this network setting. Since the scheduling problem is combinatorially complex, in the sequel, in Section 4 we present an approach to reduce complexity by restricting the set of possible scheduling and rate control decisions that the network control policy can take. In Section 5 we generalize the network topologies we consider and focus on general, multi-hop wireless networks under bursty arrivals. We consider the problem where the network control policies do not have perfect knowledge of the underlying channel conditions but take decisions only based on a, perhaps highly inaccurate, estimate. We introduce a class of policies that maximizes the stable throughput region of the network under channel uncertainty. Finally, in Section 6 we present our conclusions.

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