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Polynomial-Time Resource Allocation in Large Multiflow Wireless Networks with Cooperative Links

IZS: Invited Paper

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Abstract—An integrated multiflow network model synthesizing physical layer rate control and link layer access control is presented, permitting the study of resource allocation in large networks while allowing multi-terminal cooperation at the physical layer. We discuss how to incorporate the cooperative unit into the broader scheduling and routing framework as a “metalink,” a general notion capable of representing a variety of multiterminal physical layer topologies. Simulation results show the benefits of employing cooperative structures where needed.

I. INTRODUCTION

Increasing throughput demands have recently begun forcing synergies between previously isolated areas of the communications stack, requiring that advanced physical layer techniques—such as signal-scale cooperation—be viewed in the context of link layer radio resource management. However, the complexity associated with the merging of models results in a system unsuitable for any form of analysis. In the past, these complexities have been managed in the physical layer by ignoring all but the smallest of topologies, and in the network layer by applying an abstract view of information flows between terminals. These simplifications have enabled a large body of work to develop in the two communities, though to date complexity issues have presented a formidable barrier to the joint study of physical-layer cooperation and link-layer scheduling and routing, particularly in the context of multiflow networks.

In this paper, we will formulate an integrated model, within which we will study the scheduling and routing problem while permitting information-theoretic *rate control* on links between terminals. As we will show, this enables studying cooperative technology in the broader resource-allocation paradigm of large networks. We will discuss how this can be accomplished within our framework, and we will present results showing how cooperative resource allocation in large networks differs from the allocation in the context of conventional point-to-point links.

II. SYSTEM MODEL AND PROBLEM STATEMENT

We consider an ad-hoc half-duplex TDMA network in which all terminals share the available bandwidth. Several source-destination pairs of terminals are chosen, each demanding maximum throughput. All other terminals may participate

in the network, forwarding data in a multihop manner or in a cooperative mode, to be discussed in more detail below. We assume that all terminals have a maximum transmission power P_{Tx} , and that there is no average power constraint.

Most network-layer studies consider data to be composed of packets, which are of a predetermined size. Success of transmission is then binary: a sufficient signal-to-interference-and-noise (SINR) ratio or good proximity to the receiver guarantees that the entire packet is received. In this work, we suspend that assumption, introducing the *rate control* element to our model by describing the size of a packet using Shannon’s upper-bounding equation [1]

$$R = \log_2(1 + \text{SINR}) \quad (1)$$

for point-to-point links. For clarity of exposition but without loss of generality, we consider timeslots of 1 second and a bandwidth of 1 Hz, allowing us to view Shannon’s rate as the size in bits of a packet transmitted on a point-to-point link.

III. APPROACH AND EXAMPLE

Here we discuss our approach for allocating resources in multiflow networks with rate control, and show how this framework is amenable to the incorporation of cooperative technologies.

A. NFIC

As presented in [2], [3], we have developed a framework for performing resource allocation in large networks with multiple flows in $O(N^3)$ time. Due to space considerations, we refer the reader to our references for the details. Fundamentally, the approach hinges on a novel data structure called the *Network-Flow Interaction Chart*, which specifies the detailed interactions of data and terminals at all time instances in the network. The terminals are represented as nodes in the chart, replicated in the x direction to represent the time-slotted communication. Edges are drawn between nodes to represent transmission between two terminals at a specific timeslot. This data structure is well-suited to dynamic programming techniques, which enable us to schedule and route data for maximum throughput on a per-packet basis in polynomial time. Edges are assigned weights corresponding to the rate

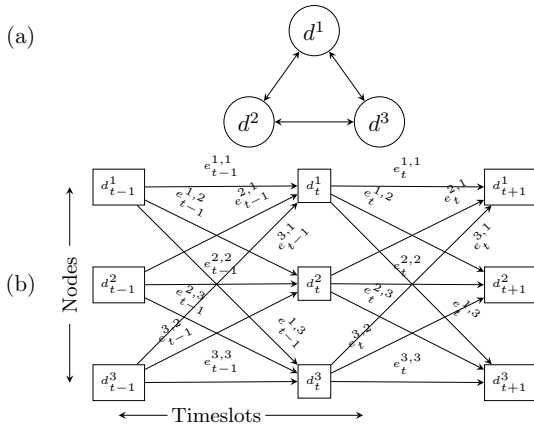


Fig. 1. An example topology (a) and the NFIC (b). Note that all nodes interfere with all others, and so the NFIC is fully connected.

achievable between the anchoring terminals at time t , and these weights are propagated through the chart by the dynamic programming algorithms. Edges are then “zeroed out” after a packet has been allocated to make them unavailable, thereby enforcing duplexing constraints. Similarly, terminals not transmitting or receiving an allocated packet have their edge values scaled down to prevent interference from affecting the existing packets. A network and corresponding NFIC is shown in Figure 1.

In order to incorporate cooperative links into the framework, we must represent the notion of data flowing to *two destinations* in one timeslot (the cooperative BC phase), and *constructively combining* in a subsequent timeslot (the cooperative MA phase) [4]. To accomplish this, we propose adding a new type of node to the NFIC framework, the metanode.

B. Metanodes

Nodes in the NFIC have, until now, represented exactly one terminal in the network. As a new class of nodes, the metanodes represent a coordinated combination of terminals, in this case the cooperative unit of a particular source, relay and destination. An edge *entering* a metanode corresponds in the schedule to data being transmitted from the source terminal to the intended destination and also the associated relay. An edge *exiting* a metanode corresponds in the schedule to the coordinated transmission of both the relay and source, where signals constructively combine at the destination. The weight on *both* the entering and departing metanode edges is set as the overall rate the cooperative unit can achieve, which (although not known explicitly) can be bounded in the time-shared relay case as [5], [6], [7]

$$\min \begin{cases} \log_2 \left(1 + P_s^{(1)} h_{sr}^{(1)} \right) + \log_2 \left(1 + P_s^{(2)} h_{sd}^{(2)} \right) \\ \log_2 \left(1 + P_s^{(1)} h_{sd}^{(1)} \right) + \log_2 \left(1 + P_s^{(2)} h_{sd}^{(2)} + P_r^{(2)} h_{rd}^{(2)} \right) \end{cases} \quad (2)$$

where P_s and P_r are transmission powers at the source and relay respectively, with channels h between all terminals

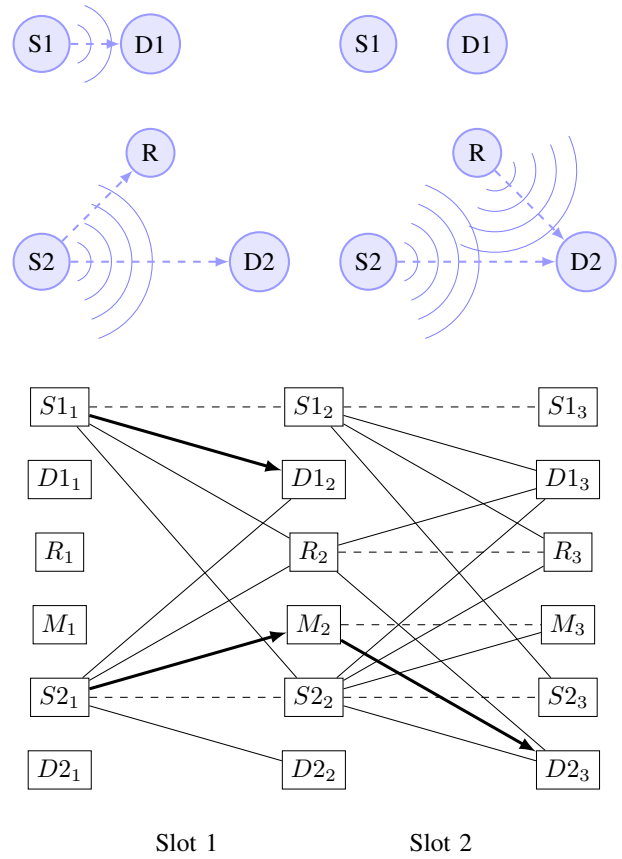


Fig. 2. Top: Network activity in timeslots 1 and 2. Both sources transmit in the first slot, their intended destinations shown by the broken lines. In timeslot 2, S_2 and R transmit together in the MA stage of cooperation. Bottom: The NFIC corresponding to this network and its activity. Note that how the metanode M describes the cooperative behavior shown above.

being similarly labeled. We require that cooperation explicitly aid the transmission, i.e. that the channel is degraded: $\min\{|h_{sr}|^2, |h_{rd}|^2\} \geq |h_{sd}|^2$. Note that we assume zero correlation between the relay and source transmissions, and that the relay channel is in the BC and MA phases for equal amounts of time.

C. Example: Metanodes in the NFIC

To illuminate the concept of a metanode in the NFIC, consider the small network of five nodes, shown in the upper pane of Figure 2. The channels are dominated by pathloss.

Here, two sources S_1 and S_2 are attempting to communicate with two matching destinations D_1 and D_2 . The NFIC corresponding to this network is shown in the lower pane of Figure 2, where we have added the metanode M to capture the notion of cooperation occurring between S_2 , R , and D_2 . In particular, the edge between S_{2_1} and M_2 corresponds to the second source transmitting, but with that transmission being received by *both* the relay node and the intended destination. The edge from M_2 to D_{2_3} then corresponds to *both* the relay and source transmitting in the second timeslot.

The NFIC routing and corresponding network activity is shown in Figure 2. Here we preserve clarity by not drawing all edges in the NFIC, rather including only those which are relevant as data emanate from the sources. Note that in the second timeslot, although only *one* edge in the NFIC is active, *two* transmissions are occurring in the network!

In this way, we are able to use the *same* polynomial-time routing and scheduling technologies as described in [2], [3] in networks where cooperation is used.

D. Choice of Metanodes: Memory Complexity

The choice of best relay terminal for a given packet route is known to be NP-hard in the general fading environment [?], which when considered jointly with the NP-hard routing and scheduling problem, results a doubly complex selection problem. In our case, choosing the metanode, the source-relay-destination triple, can be simplified with the use of geographical information. The pathloss-dominant fading environment allows us to consider only nearby terminals as potential relays. Thus, for each terminal which may act as a source, we may locally select relays and corresponding destinations. These form our metanodes, which may be incorporated in the NFIC resource allocation decisions.

Our algorithms are $O(N^3)$ in the number of nodes in the NFIC, which means that adding metanodes to each terminal does not increase the order of the complexity. However, it does increase memory requirements, as new edges and terminals are introduced to the NFIC with weights which must be stored. Table I shows memory data for the NFIC with a varying number of metanodes defined *per* terminal. Memory requirements increase considerably over the multi-hop NFIC, though since all but two edges into and out of metanodes are zero, the sparsity of the resulting NFIC is considerable. This means that even for large numbers of defined metanodes, memory complexity does not overwhelm the algorithm.

TABLE I
PERCENTAGE INCREASE IN MEMORY REQUIREMENTS OVER MULTIHOP NFIC AND SPARSITY OF NFIC REPRESENTATION

Metanodes per Terminal	Raw Storage Increase (%)	Sparsity (%)
1	300	75
3	1500	93.75
5	3500	97.22
7	6300	98.44

IV. BROADER NETWORK ALLOCATION

The use of metanodes in the resource allocation algorithm as illustrated above can be applied to much larger networks, where the polynomial-time nature of our solutions permits allocations in networks of near-arbitrary size.

A. Example

We choose to study networks in which pathloss is the dominant channel effect, but this assumption is not required for our techniques to apply. We make this choice since it helps

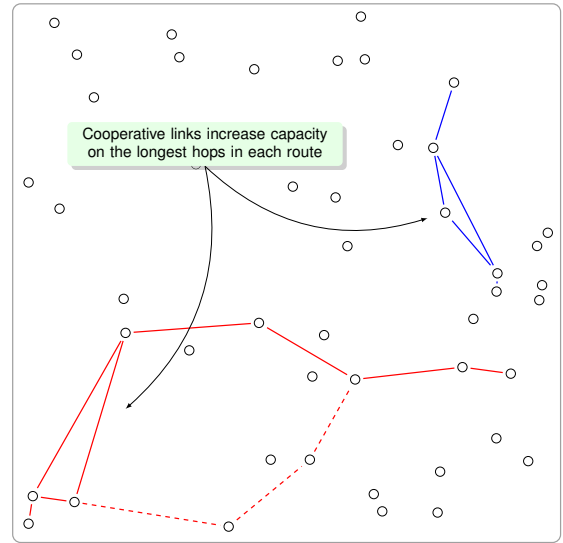


Fig. 3. Two-flow network in which NFIC resource allocation was used with metanodes available. In the allocation, metanodes corresponding to the cooperative terminals shown above were found optimal by the dynamic programming routines, and in the case of the red flow, use of the cooperative metanode completely changed the routing decision for the flow.

to illustrate where cooperative gains exist in the network. An example of resource allocation with cooperation is shown in Figure 3. Here, two flows compete for network resources, and both are able to leverage cooperative links. Since the network is dominated by pathloss, cooperation will assist the overall throughput of the flows only on the longest hop in the route, which is the throughput bottleneck.

This is clearly illustrated in the example network, where the routing decision for the red flow *changed* as a result of the cooperative metanode being available in the NFIC. Had cooperation not been available, the red flow would have followed the sequence of terminals indicated by the broken line.

B. Simulation Results

1) *Cooperative Benefits in Large Networks*: To compare the benefits of NFIC-Metanode resource allocation to multihop routing, we simulate networks and allocate resources under the two different paradigms. We assume a pathloss-dominated channel environment. We study the mean throughput for a varying number of flows in the region, where the schedules and routes have been calculated using NFIC techniques. Shown in Figure 4 is a comparison of throughputs for two pathloss environments, free space ($\alpha = 2$) and urban ($\alpha = 4$) as a function of the number of flows demanding resources. The solid lines are mean flow throughputs when three metanodes per terminal are included in the NFIC, allowing the algorithm to exploit cooperative technologies where needed. The broken line indicates throughputs for multi-hop only allocation.

We observe improvements over multihop in both environments and for all levels of congestion, though the improvements are most pronounced with low pathloss and few flows,

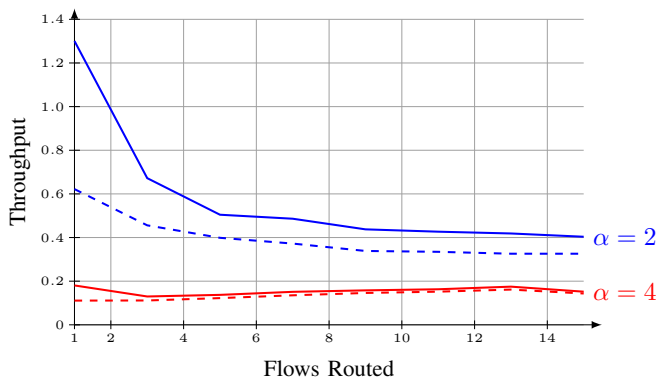


Fig. 4. Mean throughput for networks with cooperative links (solid) and multihop-only routes (broken). Cooperative links, represented by metanodes in the NFIC, considerably increase throughputs for low-pathloss environments, especially when only few flows are competing for resources.

where datarates can increase by a factor of 2. Gains diminish for higher pathloss and as congestion increases, since cooperative gains are affected by the overall-higher interference temperature in the network.

2) *Number of Metanodes*: As discussed above, the number of metanodes chosen for the NFIC affects memory complexity, but it also affects the resource allocation selected. If a relatively small number of metanodes are defined, they may not be useful in the routes required by the flows. Increasing the number of metanodes defined per terminal does increase memory requirements, but also makes cooperative links available to more parts of the network. It is interesting to study network performance as a function of how many metanodes are defined for each terminal in the network.

Figure 5 show this relationship. For each terminal, we define a number of metanodes using local relays as described above, and calculate a resource allocation for that topology with two information flows. We then redefine more metanodes and recalculate the allocation, plotting the mean throughput for the flows as a function of number of metanodes we have defined. This is repeated for a thousand topologies, and average results are reported. Throughput increases considerably if more metanodes are defined in the case of low pathloss, less so if pathloss is high. This is because the throughput on a route is determined by the “bottleneck link” which, once aided with cooperation, may remain the cooperative link. This is the case in high-pathloss environments, where the cooperative advantage is smaller. Cooperative units are much more effective in lower-pathloss environments, where all three channels are stronger.

V. CONCLUSION & FUTURE CHALLENGES

We have presented a model for wireless networks which captures the salient issues in both physical layer and network layer resource allocation, namely those of rates, schedules, and routes. We have shown how this model can be extended to incorporate cooperative transmissions, and we have used

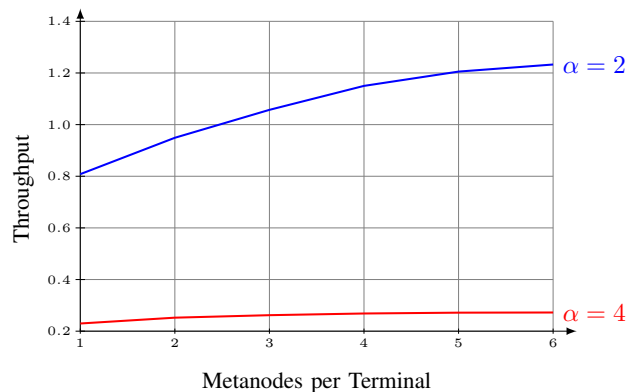


Fig. 5. Mean throughput of two flows as a function of the number of metanodes defined for each terminal in the network. More metanodes are helpful in low-pathloss regimes, though they do increase memory requirements.

our polynomial-time NFIC allocation technique to show the clear benefits of using cooperation where needed.

Open questions remain, especially in the domain of choosing metanodes. Our geographically localized technique employed here shows benefits, but is heuristic and unoptimized. To maximize the gains possible with NFIC-metanode resource allocation, those metanodes must be carefully selected according to an optimized technique.

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