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Distributed multi-objective cross-layer optimization with joint hyperlink and transmission mode scheduling in network coding-based wireless networks[☆]

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ABSTRACT

In this work, we address a cross-layer multi-objective optimization problem of maximizing network lifetime and optimizing aggregate system utility with intra-flow network coding, solved in a distributed manner. Based on the network utility maximization (NUM) framework, we resolve this problem to accommodate routing, scheduling, and stream control from different layers in the coded networks. Specially, we consider that there are two scheduling primitives, namely hyperlink and transmission mode, to be concurrently activated for the multi-objective optimization. Given the constraints with respect to these primitives, the optimization problem is specifically formulated as a quadratically constrained quadratic programming (QCQP) problem that is NP-hard in general, and its scheduling subproblem even when reduced to account for only one of these primitives is a maximum weighted independent set (MWIS) problem that is NP-hard already. To alleviate this complex problem in a distributed manner, we resort to alternate convex search (ACS) and primal decomposition (PD) to approximate the optimal results by using biconvex programming model and subgradient-based algorithm that can iteratively approach to the optimal solution. For the wireless multihop networks, wherein an optimal solution could be practically approximated as its validity would be out-of-date soon in the error-prone wireless environment, our simulation results show that the distributed method can fulfill our requirements, and can make a good trade-off on the heterogeneous objectives with well computational efficiency.

1. Introduction

Recent proliferation of wireless services has created large scale demands for transmission of traffic requiring stringent throughput guarantees, and the system performance of such networks is typically a function of the amount of data collected by individual stations and delivered to a set of sinks through multi-hop routing. However, these stations usually operate with small batteries that are difficult to replace in typical scenarios, and thus minimizing their energy consumptions and maximizing the network lifetime continuously intensify the interest of researchers in the development of energy-efficient wireless transmission schemes. Further, a trade-off inevitably arises in simultaneously maximizing the network lifetime and the application performance. For this challenge, a cross-layer optimization scheme is usually adopted by the related works because it can coordinate resources allocated to different layers to achieve globally

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optimal performance for various objective functions. Nevertheless, due to the nature of wireless multihop transmission, distributed algorithms for, e.g., routing and scheduling, are more practical than the cross-layer optimization counterparts that would be usually operated in a centralized manner. Thus, how to preserve theoretical benefits from a centralized optimization method while adapting to the distributed computation environment motivates our research to develop decentralized approaches based on mathematical programming models.

As another perspective of research, Ahlswede et al. introduce in their seminal work [1] that by allowing intermediate nodes to perform coding operations in addition to pure packet forwarding, network coding (NC) can achieve the maximum multicast rate and thus can improve the overall network throughput. Following that, Li. et al. [2] show the fact that linear network coding suffices to achieve the maximum rate, and further Ho et al. [3] show that random linear codes can be used to achieve the linear network code rate asymptotically. More explicitly, the wireless broadcast nature enables a wireless station to broadcast data to all neighboring nodes. Each station or node can then overhear packets from the multicast source or any neighboring nodes, and act as a *router* or *forwarder* to forward data to multicast destinations. Nevertheless, caused by lossy wireless channel, different nodes could overhear the packets from the same router but might lose different packets, thus requiring the router to retransmit the lost packets. To resolve this issue, the authors in [4,5] exhibit intra-flow network coding for loss recovery of multicast traffic, and show that the number of retransmissions required for loss recovery is significant reduced.

Now, given the capability of network coding, it still remains significant challenges for a cross-layer optimization in wireless multihop networks even with centralized approaches. For example, it had been readily shown in [6–8] that the general problem of interference-free scheduling for multihop wireless networks is NP-hard to a centralized algorithm even without network coding. Here, by adopting intra-flow NC to extend the capability of routing while addressing the other problems arising from different layers, we face an even more challenging scheduling subproblem in the coded networks wherein each hyperlink (or hyperarc in [9]) has different probability to be activated and each transmission mode (or network component in [10]) has different probability to be selected for operation among the various trade-offs between throughput and lifetime utilities in a joint objective function, which should be determined simultaneously for both hyperlink and transmission mode, and all have to be done in a distributed manner consistently.

Related works. In the following, we review related works in four categories: joint cross-layer optimization, scheduling design, resource allocation on NC, and other related works.

1) Joint cross-layer optimization. For wireless sensor networks (WSNs) without NC, the authors in [11] study the problem of joint routing, link scheduling and power control to support high data rates and propose an algorithm to minimize the total average energy consumption in such networks. In [12], the authors consider a joint optimal design of physical, MAC, and routing layers to maximize the lifetime of WSNs. Specifically, they use TDMA as their MAC to formulate the optimization problem as a mixed integer convex problem, which can be solved with standard techniques such as interior point methods. In addition, the authors in [13] develop a unifying framework to understand the trade-off between the application layer performance and the lifetime of a WSN in which nodes can adopt their source rates so that the network operates at an optimal set of source rates that can jointly maximize the network utility and lifetime. In addition, many other cross-layer solutions for WSNs can be found in the survey paper [14].

2) Scheduling design. As a seminal work on scheduling, Tassiulas and Ephremides [15] obtained a link scheduling policy that attains the maximum possible throughput in presence of arbitrary scheduling constraints, by scheduling in each time slot an independent set (in the link interference or conflict graph) that has the maximum aggregate queue length. Afterward, the maximum weighted independent set (MWIS) problem of finding the independent set with the maximum weight involved is known to be a bottleneck of the wireless utility maximization problem [16]. As noted in [17], the scheduling-relevant formulations often suffer from two shortcomings: 1) the optimization problem could be intractable when the network size is large (i.e., it is NP-hard), and 2) the optimization problem could be amenable to centralized implementation only.

3) Resource allocation on NC. By randomly mixing a sequence of native packets in the same multicast session together, the empirical study [4] also shows that intra-flow or inter-session NC can be MAC-independent and have the practical benefits of mixing packets with low complexity. Given that, for an unicast traffic problem with intra-flow NC, the work [18] proposes a rate control scheme to control the forwarding data rate and improve NC efficiency under a fixed physical bit rate. A similar optimization problem in [19] has also been investigated for unicast traffic but further extended to solve the problem of adapting the transmission bit rate of each node. Apart from the above, certain aspects about subgraph selection for intra-flow multicast NC have been already revealed and summarized in [9].

4) Other related works. Complementing the approaches categorized above, there are other related works still worth mentioned here. For example, the problem of achieving min-cost multicast in networks has been studied [20], and the rate control problem for the multicast flows had been addressed [21], all by means of network coding. As a very useful tool, game theory is also utilized to accommodate the framework of network coding to achieve the maximum multicast in WSNs. Specifically, the work in [22] shows that a generalized butterfly network can be analyzed as a two-source unicast coded network, and its robustness had been investigated by game theory with the desired solution to reach equilibrium. In addition, the authors in [10] jointly consider links, routes, and network components with a nonlinear cubic game, and constitute an unconstrained optimization problem to be sequently solved with a fictitious play (FP) technique. Recently, in [23] we propose a cross-layer optimization formulation to jointly maximize two different performance utilities in wireless multihop networks with network coding. However, the previous work only considers for transmission modes, in contrast to the distributed approach presented here that accounts for both hyperlink and transmission mode. In fact, these metrics (transmission mode and