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Cross-layer optimization of wireless multihop networks with one-hop two-way network coding

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ABSTRACT

In this paper, we investigate optimal cross-layer design of congestion control, routing, one-hop two-way inter-commodity (OTIC) network coding and scheduling in wireless multihop networks utilizing the broadcast advantage of wireless medium. We first present an achievable rate region with OTIC network coding by introducing virtual flow rates in a node. Then we formulate the network utility maximization problem subject to constraints on this achievable rate region, and analyze the complexities of both node- and path-based formulation with no network coding, OTIC network coding, and overhearing network coding. After that, we solve it using dual decomposition and subgradient method. Based on the solution, we present a new queue model, which is able to facilitate the coding operation between two-way commodities, and then propose a backpressure-based cross-layer optimization algorithm with low coding complexity and overhead. Afterwards, we analyze the stability and asymptotical optimality of the proposed cross-layer algorithm by Lyapunov drift technique, and evaluate its performance through extensive simulation. By comparing with the pure routing scheme under both primary and two-hop interference models in an illustrative topology, it is shown that with the proposed joint optimization algorithms, the OTIC network coding can interact adaptively and optimally with other components in different layers and achieve high throughput gain. Simulation of the proposed algorithm in a mesh network with base station and a random ad hoc network justifies that OTIC network coding can obtain considerable throughput gain with low complexity in various kinds of networks.

1. Introduction

Network coding (NC) has emerged as a promising technique to efficiently utilize the resource of both wired and wireless networks. The key idea of network coding is to give routers the ability of data processing besides pure forwarding. In general, there are two kinds of network coding categories: intra-session network coding and inter-session network coding. Intra-session network coding only allows coding packets from the same session, while inter-session network coding is to consider coding opportunities among different sessions. It has been shown that network coding can achieve significant performance gain in both wired and wireless networks. Ahlswede et al. [1] proved that the maximum capacity of a multicast session, i.e., the max-flow or min-cut of the network, can be achieved through intra-session network coding. Katti et al. implemented an opportunistic network coding using XOR in an 802.11-based wireless ad hoc network, and achieved up to 400% throughput gain in a practical network [2].

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Although use of NC can achieve significant performance gain, optimal integration of NC, especially inter-session NC, into the existing architecture of a network is not straightforward. NC cannot be performed as an independent function in a specific network layer, and it will influence all functional components in current network protocol stacks, for instance, scheduling, routing and congestion control, etc. Optimal control of wireless multi-hop networks with NC has to consider the interaction of NC with all of those functions.

1.1. Network coding and scheduling

In scheduling-oblivious network coding approaches, e.g., COPE [2], NC is carried out whenever a coding opportunity is identified. However, this aggressive network coding approach may not be optimal in a wireless multi-hop network, since the multicast rate after network coding is determined by the link with the minimum rate, while there exist interference and probable rate asymmetry among neighboring links. Therefore, we have to consider the influence of the scheduling mechanism when designing network coding in certain wireless networks [3].

1.2. Network coding and routing

Since wireless channel is inherently broadcast and spatial channel reuse is restricted, routing selection without NC has to avoid interference among neighboring links to obtain better performance in terms of throughput or delay, etc. However, when NC is introduced, paths should be chosen to be near enough in order to create more coding opportunities for different sessions. Henceforth, a tradeoff needs to be made between coding and interference avoidance in wireless multihop networks. It has been shown that joint optimization of both routing and network coding can attain significant performance gain [4].

1.3. Network coding and congestion control

Network coding (NC) can be used to alleviate the congestion of some bottleneck links at the cost of increased computational complexity or overhead. However, it is not necessary to apply network coding on links that are not congested in order to keep low operational complexity. Therefore, to fully utilize the benefit (throughput gain) and cover the shortage (complexity) of network coding, it also needs to be congestion aware and interact with congestion control adaptively [5].

Recently, solid work has been done on cross-layer optimization of wireless multihop networks with inter-session network coding. With predetermined routing, joint optimization of scheduling and network coding proposed in [2] is analyzed and a backpressure-based optimal policy is proposed in [3]. Joint routing and network coding [2] has been analyzed theoretically using linear programming in [4], and it is shown that coding and interference-aware routing yields much higher performance gain than coding-oblivious ones. However, no congestion is considered in [4] and the formulation is *path*-based, the complexity of which increases exponentially with the number of nodes. Energy cost minimization using cross-layer optimization with network coding is investigated in [6]. However, only energy minimization without network coding is formulated, and the routing is coding-oblivious and needs complicated queue search. Joint network utility optimization and network coding (pairwise inter-session network coding (PINC) [7]) is formulated and solved in [5]. However, it is formulated from *path* perspective, and the solution is centralized.

To the best of our knowledge, no research has been seen on optimal and distributed cross-layer design of network coding taking into account all layers and low complexity. In this paper, we incorporate scheduling, network coding, routing and congestion control into cross-layer optimization framework, formulate the problem from *node* perspective to lower the complexity, and propose a novel queue structure and an easy-to-implement algorithm in order to realize the cross-layer optimization in a distributed manner.

Since pairwise network coding (PINC) [7] is constructed based on all possible paths from source to sink nodes, and whether it can be built from node perspective is still unknown, we adopt the network coding scheme COPE [2] in the present work. In addition, to simplify the analysis, we only consider the one-hop two-way inter-session (OTIC) network coding of COPE, and leave incorporating opportunistic listening to be done in the future work. In fact, wireless NC without opportunistic listening is more feasible for multi-hop wireless access networks where there are lots of such two-way flows at intermediate nodes, e.g., routers in wireless mesh networks and relays in relay-assisted cellular networks. Although OTIC is a special network coding scheme of COPE and PINC, our work is different from others in both problem formulation and solution. Furthermore, we can also include opportunistic listening in a coding-oblivious way with additional complexity as in [6].

Backpressure is a very useful and efficient method to solve the multi-commodity problem [8,9] and has also been used to solve the network optimization with network coding [4]. However, the solution in [4] cannot be applied directly to the problem formulated in this paper, since it is coding-oblivious and needs complicated queue search. When routing also needs to be jointly optimized with network coding, it is inefficient to directly utilize the same backpressure policy. Hence, in this paper, we develop a new queue model to utilize backpressure method to realize optimal cross-layer control with reduced complexity. The queue model proposed here is based on the achievable rate region of network proved by introducing a new parameter, virtual flow rate, which is the rate of locally transferring packets to the unicast output buffer from other input ones.

The rest of the paper is organized as follows. More related work is presented in Section 2, and preliminary definitions as well as network model, network coding and link capacity are introduced in Section 3. After that, we discuss the achievable rate region by introducing virtual flow rates in Section 4, and formulate the network utility maximization problem and solve it using dual subgradient method in Section 5. Then we present the new queue model and the backpressure algorithm in Section 6, analyze and evaluate the performance of the algorithm in Sections 7 and 8, respectively. The whole paper is concluded in Section 9.