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Price-based congestion control and local channel-link assignment for multi-radio wireless mesh networks ☆

Wonyong Yoon [a,*], Dongman Lee [b], Byoungheon Shin [b], Seon Yeong Han [b]

[a] Department of Electronic Engineering, Dong-A University, Hadan-dong 84, Saha-gu, Busan, Republic of Korea
[b] Department of Computer Science, KAIST, 291 Daehak-ro, Yuseong-gu, Daejon, Republic of Korea

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ABSTRACT

In multi-radio multi-channel wireless mesh networks, engineering the network capacity requires a complex cross-layer design. In this paper, in order to make the complex problem implementable in a distributed manner, we make a decoupling approach that breaks down the entire design space into routing and initial channel assignment, and distributed congestion control and local channel reassignment. We propose a unified priced-based framework for distributed congestion control and localized channel-link assignment algorithms. We demonstrate the convergence of the proposed algorithms with respect to different fairness objectives (i.e., proportional fairness and max–min fairness) via simulation on both grid and random topologies. The proposed algorithms achieve faster convergence with less overhead in the control and forwarding plane than previous multi-path based algorithms.

1. Introduction

Engineering the capacity or throughput of emerging multi-radio multi-channel wireless mesh networks that use IEEE802.11 commodity radios should involve a cross-layer design of all the protocol stacks, from scheduling at the medium access control (MAC) layer to channel assignment at the link layer, routing at the network layer, and congestion control at the transport layer. More specifically, for a flow, we need to determine how much portion of packets of a flow will traverse which end-to-end route (path), which channels to be used on each link, and how much portion of capacity of each link and channel pair will be utilized for each flow. Pursuing an optimal solution to maximize the network utility is computationally infeasible, and thus most previous works have focused on a subset of design perspectives to derive feasible and implementable solutions [1–6]. Ramachandran et al. [2] propose using static channel assignment for mesh networks with more than two radios where some interfaces are fixed to a common channel for connectivity of networks. Kyasanur et al. [3] propose hybrid channel assignment and a new routing metric that accommodates channel switching delay in on-demand routing. Giannoulis et al. [4] propose clique-based congestion control and channel assignment algorithms in multi-radio wireless mesh networks. Since they consider all possible multi-paths for a flow and all cliques existent in a network, these algorithms are not amenable to distributed implementation due to the resulting complexity. Shi et al. [5] deal with the problem of routing, channel assignment, and power allocation with assumption of a *single* full-duplex cognitive radio interface. Their distributed algorithms though with complex iterations can increase the scaling factor of flow rate requirements, but do not consider fairness in congestion control. Tang et al. [6] consider various fairness objectives for rate control in multi-channel wireless mesh networks, but their linear programming and convex programming based approaches are centralized.

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* Corresponding author. Tel.: +82 51 200 7716.
E-mail address: wyyoon@dau.ac.kr (W. Yoon).

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We focus on network throughput in multiple commodity radio mesh networks based on *quasi-static* channel assignment where a fixed channel of a link is statically used for each flow until next channel re-assignment. Our previous work [7] shows that exploiting dynamic link quality measurement in a local distributed way enables each link to use a better channel with higher expected link throughput, and hence the whole network can make better use of multiple available channels. In this paper, we enhance the dynamic link quality awareness mechanism [7] by conjunction with a price-based congestion control (or rate control) algorithm that enables determination of network throughput in regards to a selected fairness objective. Price-driven congestion control in a network utility maximization framework has been widely used for resource allocation in wireless networks [8]. We make the first, to the best of our knowledge, attempt to gracefully apply the price-based approach to multi-radio multi-channel wireless mesh networks and introduce a necessary dimension and related parameters to the new problem setting. Our proposed congestion control algorithm uses newly dimensioned price information for each pair of a link and a used channel, and serves as a unified distributed framework for different fairness objectives. The price information can also help reduce the overhead of the dynamic link quality awareness mechanism.

The remainder of this paper is organized as follows. In Section 2, we summarize previous related works and highlight the contribution of this paper. In Section 3, we formulate congestion control problems with two different fairness objectives in wireless mesh networks. In Section 4, we describe the details of proposed distributed solutions to the formulated problems. In Section 5, we demonstrate the convergence property of the proposed solutions, and also provide a performance study in random topologies and a comparison study with other approaches. In Section 6, we make final remarks.

2. Related work

Multi-radio multi-channel wireless mesh networks pose complex design issues across various layers of the protocol stack (from congestion control to routing, channel assignment, and link scheduling). Some previous works have dealt with congestion control as one of problem scopes. Giannoulis et al. [4] deals with congestion control and channel assignment in multi-radio multi-channel wireless mesh networks. They consider multi-path routing for a flow and thus, all possible sub-paths with different sets of intermediate routers and different sets of channels for links are formulated in a utility maximization problem. The multi-path feature requires an addition outer loop for convergence to optimal fair flow rates, and may make the formulation computationally infeasible owing to exponential numbers of possible sub-paths for each flow. Tang et al. [9] formulate various fair rate allocation problems in multi-radio multi-channel networks in the form of linear programming and convex programming. They show that the problems are NP-hard and propose a heuristic algorithm which is centralized and needs global information. The algorithm allows multiple sub-paths, which may suffer from exponential complexity during computation. The algorithm is not based on the network utility maximization (NUM) framework for convergence, and thus it is not adequate for distributed implementation.

There are another avenue of previous works that do not take congestion control into account in multi-radio multi-channel wireless mesh networks. Ning et al. [10] focus on devising link-layer metrics for scheduling and network-layer metrics for routing. They try to ensure fairness among links and give a higher routing priority to links with less congestion and larger queueing for improving throughput. Their solution is centralized and considers fairness in terms of links but not flows. Ramachandran et al. [2] focus on dynamic channel assignment that minimizes interference in multi-channel wireless mesh networks. The algorithm is centralized and requires interference estimation at each distributed mesh router.

There are some recent works that focus on other aspects of multi-radio multi-channel networks than throughput or network utility. Avallone et al. [11] consider energy efficiency in addition to network utilization. They formulate a novel energy efficient channel assignment and routing problem and propose a heuristic algorithm for maximizing the number of radios turned off while achieving the best total utilization. The algorithm is centralized and not based on the NUM framework. Jahanshahi et al. [12] focus on a multicast transmission problem in multi-radio multi-channel networks. They formulate a novel binary integer programming model with an objective of minimizing the total number of links together with the total interference. In the model, multicast tree construction and channel assignment are jointly considered to minimize interference. The proposed approach is not based on the NUM framework, and instead should use a centralized linear programming solver.

2.1. Contribution

Our work in this paper makes some new contributions. First, we take a single-path and single-channel-link approach to enable *distributed* implementation of congestion control and local channel link assignment, which is a departure from previous centralized approaches [1,4,9] in multi-radio multi-channel wireless mesh networks. In our approach, distributed channel link price information intervenes between distributed congestion control and local channel link assignment, and serves as an enabler for convergence to fair rate allocations at a given instance of channel assignment. Second, we explicitly demonstrate fair rate *convergence* in multi-radio multi-channel networks through simulation, whereas previous works have only presented the values of total allocated rates and have not described convergence behaviors [4,9]. Third, we show that a single price information can serve as common control information to achieve different fairness objectives (proportional fairness and max–min fairness), and use it to form a *unified* price-based framework for various fairness criteria. Fourth, the pro-