Distributed Resource Allocation Extending Capacity of Wireless Networks

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1. Introduction

As social networking and mobile advertising become popular, multimedia traffic over mobile communication networks surges. In wireless networks, where resources are scare due to limited bandwidth, low-processing power, restrictions on transmission power and energy, wireless interference, high demands for such a large amount of data will force the network system to operate under heavy traffic load near its capacity boundary.

Recent advances in communication technology enable wireless networks to exploit various diversities from system dynamics, which can lead to significant capacity improvement. For example, it has been shown in single-hop wireless networks that overall network performance can increase by opportunistically scheduling links accounting for states of fading channels [1]. The idea has been extended even to multi-hop scenarios [2-5]. However, these solutions are often impractical to implementation due to complex control with intensive computations and requirement of centralized coordination to collect global information of network states, which is often unavailable in multi-hop wireless networks. Hence, low-complexity distributed resource allocation schemes that can opportunistically utilize network resources and that can achieve performance gains from such diversity still need to be developed. To this end, we focus on scheduling, one of network functionalities with the highest complexity, in multi-hop wireless networks, and study opportunities and challenges for development of efficient resource allocation schemes that use only local information.

2. Efficient Resource Allocation Schemes

Tassiulas and Ephremides showed in their seminal work [6] that the optimal throughput performance can be achieved by scheduling links with the largest queue weighted rate sum. The algorithm known as the Maximum Weighted Scheduling (MWS) policy solves the following problem:

$$\vec{r}(t) = \underset{\vec{r}(t) \in S}{\operatorname{argmax}} \sum_{l \in E} q_l(t)\, r_l,$$

where S denotes the set of all feasible schedules, $q_l(t)$ denotes the queue length of link l at time t, and $\vec{r}(t)$ denotes the link rate vector in the feasible schedule. We note that a schedule is feasible if all links in the schedule are non-interfering with each other. In most network scenarios, these interference constraints between links are very complex, and the set of feasible schedules is non-convex and of enormous size. It has been shown that the above problem is in general an NP-Complete problem [7].

A suboptimal scheduling called Greedy Maximal Scheduling (GMS) has been proposed to reduce the complexity. At each time t, it schedules a set of links l that are chosen in decreasing order of the queue weighted rate $q_l(t)r_l$ while conforming to the interference constraints. GMS provides a constant fraction of the optimal performance, and empirically achieves the optimal performance under a variety of network settings [8]. However, it still requires organizing link activities in a centralized manner.

In multi-hop wireless networks, low-complexity algorithms that are amenable to distributed implementation are desirable. In this direction, many scheduling algorithms have been developed. Randomized Maximal Scheduling (RMS) is one of them. A maximal schedule is a feasible schedule that no link can be added to without violating interference constraints. RMS randomly uses one of the maximal schedules. RMS also achieves a guaranteed fraction of the optimal throughput performance [9], which depends on the underlying network graph.

Toward optimal performance in general network graph, a class of scheduling schemes called Pick-and-Compare has attracted attention [10, 11]. A policy in this class picks a schedule at random, evaluates this and the current schedule by comparing their queue weighted rate sum, and chooses the one with the larger sum as the next schedule. A weakness of this approach is that the comparison process often incurs a large amount of message exchanges. This problem has been addressed by recently developed Carrier Sensing Multiple Access (CSMA) based scheduling policies [12, 13], which successfully replace the time-consuming comparison procedure with evolution of Markovian process using carrier-sensing functionality. Both Pick-and-Compare and CSMA based approaches suffer from high complexity and/or high packet delays.

Another class of distributed scheduling schemes, called Queue-length based Random Access Scheduling policies, relies on local message exchanges to resolve contention [8, 14]. By adjusting each link's attempt probability based on queue information in the link's neighborhood, it provides explicit tradeoffs between efficiency and complexity.

Although these distributed solutions are efficient, they have been designed under many assumptions that ignore important recent advances in wireless communication. Their extension to new technologies will be non-trivial, since their performance often relies on long-term evolution of the system, while many advanced radio techniques exploit instantaneous changes of system states.

3. Opportunities and Challenges

Efficient distributed scheduling can be developed using novel methodologies to exploit various wireless diversities. These diversities can originate from opportunistic scheduling, cooperative communications, multi-carrier multi-channels, and smart antennas.

- Opportunistic scheduling: the optimal solution that opportunistically utilizes the time-varying link rates has been developed by scheduling the set of links that maximizes the queue-weighted rate sum. However, in multi-hop networks, scalability and implementability demand that a low-complexity decentralized solution be developed. Hence, how one can design efficient scheduling solutions that operate in a distributed manner is an interesting open question.

- Multiple-input and multiple-output (MIMO): the use of multiple antennas at both the transmitter and the receiver end promises significant performance improvement in throughput and/or transmission range through spatial multiplexing. From a networking perspective, sub-channels (or streams) can be selectively used for efficient communication.

- Cooperative communication: multiple links can cooperate to strengthen the received signal enhancing throughput by allowing high-rate modulation and coding schemes. Thus it can protect against packet losses in noisy wireless environment and provide new opportunities for efficient resource usage, improving capacity close to information theoretical bounds.

- Smart antenna (directional antenna): signal radiation can be formed accordingly to control transmission power and interference between adjacent transmissions. By leveraging spatial locations of the transmitter and the receiver, smart antenna allows multiple capacity pipes to coexist in the same frequency band.

Although these communication techniques boost the efficiency of radio spectrum, they add further complexities to the networking level, and incur additional difficulties in designing scheduling policies, especially, for systems that require distributed control. Therefore, we need to investigate the impact of new wireless diversities on network performance, where the diversities become available from practical issues or recently developed communication tools, and characterize the capacity improvement. Moving from centralization to distributed control, there are many practical issues including synchronization, information distribution, imperfect channel separation, and distributed decisions. They will be major challenges to practical application of new radio technologies. Studying fundamental difficulties in their practical implementations, we should design novel system architecture and scheduling algorithms that are amenable to distributed implementation as well as achieve high efficiency and low complexity.

4. Summary

Transfers of multimedia traffic over wireless networks are challenging due to limited resources available to wireless nodes. To extend network capacity close to the theoretical bounds, we need to investigate the impact of recently developed communication technologies that exploit wireless diversities on overall network performance in a networking perspective. In this paper, we overview the-state-of-the-art efficient resource allocation schemes of scheduling in multi-hop wireless networks, and explore the possibility of significant performance improvement from promising wireless communication techniques such as opportunistic scheduling, MIMO, cooperative communications, and smart antennas.

Acknowledgement
This work was in part supported by Education and Research Promotion Program of KUT.

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