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Scalable and robust channel allocation for densely-deployed urban wireless stations

Hirozumi Yamaguchi[a,*], Akihito Hiromori[a], Teruo Higashino[a], Shigeki Umehara[b], Hirofumi Urayama[b], Masaya Yamada[b], Taka Maeno[c], Shigeru Kaneda[d], Mineo Takai[a,d,e]

[a] *Graduate School of IST, Osaka University, Suita, Osaka 565-0871, Japan*
[b] *Sumitomo Electric Industries, LTD., Osaka, Japan*
[c] *Space-Time Engineering Japan, Inc., Tokyo, Japan*
[d] *Space-Time Engineering, LLC., Los Angeles, CA, USA*
[e] *University of California, Los Angeles, USA*

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ABSTRACT

This paper presents a scalable and robust scheduling algorithm for a set of wireless stations. Recently, road-side access points for vehicular networks and outdoor WiFi stations are deployed in wide urban areas and compete with each other for limited wireless resources. We focus on pursuing the best balance among (i) optimality of resource utilization, (ii) robustness to new station installation and traffic demand, and (iii) scalability to the population of stations and area size. The algorithm is designed based on a vector space theory with correctness proof. Compared with our previous work that presents the basic algorithm and theory, we extend the algorithm to a multi-layer (*i.e.* hierarchical) version to handle more realistic situations. Additionally, we have conducted extensive simulations with a variety of scenarios. Finally, the applicability of approach has been testified by a case study on a scheduling problem for roadside access points of vehicular networks in cooperation with a manufacturing corporation.

1. Introduction

Cellular networks have been successful to cover worldwide locations. Besides high speed 3G/4G cellular networks (*e.g.* LTE and WiMAX) that widely cover both urban and rural areas, a number of short range wireless stations are covering urban areas nowadays. For instance, outdoor public Wi-Fi access points (APs) have been deployed by AT&T, Time Warner Cable, etc. to offload smartphone 3G or 4G traffic in large cities of US. In Japan, high-traffic volume in 3G/4G cellular networks is the most critical issue, and the three major mobile operators have already provided Wi-Fi services for cellular subscribers. For Intelligent Transport Systems (ITS), installation of DSRC (Dedicated Short-Range Communication) road-side units at intersections and on highways and city streets has been started in Japan for vehicle collision warning, local traffic information broadcast and so on. Those APs or road-side units, which we call *stations* hereafter, are usually densely-deployed to accommodate more clients. However, dense deployment of stations may cause severe and undesired wireless interference among them. In the previous ITS example, if we require guaranteed quality of service toward vehicles within

* Corresponding author.
E-mail address: h-yamagu@ist.osaka-u.ac.jp (H. Yamaguchi).

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240 m distance from a road-side unit with 20 dB SINR threshold in 760 MHz band, each station interferes with two or three (or more) stations in each direction (*i.e.* 700–800 m interference range) in the area of Osaka downtown.

A number of studies have been dedicated to resolve wireless interference problems in a variety of networks such as cellular networks, wireless mesh networks (WMNs) and wireless sensor networks (WSNs). In these approaches, scheduling algorithms have been proposed to reuse the wireless resources (either of time slots or wireless channels). That is, a channel or a time slot is concurrently used by two or more stations if they do not interfere with each other. In cellular networks, systematic resource allocation to hexagonal cells is a well-studied topic [1]. In WMNs or general wireless multi-hop networks, link scheduling is designed based on given network topology or interference graphs, and routing performance is often considered simultaneously [2].

However, most of these methods consider scheduling for individual stations and thus scalability and robustness issues may not be solved in urban scenarios. Firstly, it is quite expensive to gather interference information from a number of stations in city-wide areas. Therefore, some conventional link-based scheduling may not scale to the number of stations and size of the areas. Furthermore, some may not be robust to new station installation and traffic demand changes. Even for rapid growth of station population and traffic volume, we would like to maintain the current allocation. Generally, administrators are often required to verify that their systems and services work properly with new configuration of allocations. However, such verification and inspection usually needs additional cost.

In this paper, we deal with a scheduling problem of wireless stations in urban areas. We assume densely-deployed stations like outdoor Wi-Fi APs and road-side stations, which are subject to location changes, new station installation and so on. In order to allocate limited resources efficiently to a number of stations in a robust and scalable manner, we employ not a station-based but cell-based scheduling and provide a near-optimal algorithm. In the algorithm, we divide the area of interest by cells, and estimate "inter-cell interference", which is an abstract representation of multiple (and potential) interference relationships among stations in cells. It hides minor difference of signal propagation among individual stations and allows us to focus more on intrinsic features of interference that are often seen in urban environment. Based on this feature, we propose a novel cell-based algorithm called *Vector-based Cell Cover (VCC)*. VCC first extracts a Common Interference Pattern (CIP) among cells and achieves near-optimal resource allocation. Then it considers irregular part and irregular traffic demand to finalize the allocation of resources to each station. As the derived resource allocation rule is fully based on cell locations, resources can be allocated to stations without consulting the other allocations. This feature provides robustness to new station installation and traffic demand changes, as well as scalability to the population of stations and area size. We also pursue optimality of resource utilization by the CIP-based sub-algorithm, which is designed based on a vector space theory with correctness proof.

Experiments by simulations have been conducted to observe the performance. Compared with two heuristic approaches that are tuned to achieve reasonable optimality using all the detailed inter-station interference information, the proposed VCC algorithm could achieve much better utilization of wireless resources while achieving robustness to new station installation. Furthermore, in cooperation with Sumitomo Electric Industries, the algorithm is applied to a real world scenario where TDMA scheduling of road-side units is required for I2V (Infrastructure-to-Vehicle) wireless communication. Our algorithm could achieve desired time slot scheduling satisfying constraints on bandwidth limitation in the designated frequency (*i.e.* 760 MHz $\pm$ 5 MHz band).

We would like to note that compared with our previous work in ACM MSWiM2013 [3] that presents the basic algorithm and theory, we provide in this paper an extended version of the algorithm to handle more realistic situations where station density is not uniform and so on. Also many new results of experiments have been added to validate our approach in different situations.

2. Related work

2.1. Spectrum usage

A number of research contributions have been dedicated to manage and schedule radio frequencies in cellular networks. For example, Fractional Frequency Reuse (FFR), which allocates different frequencies to users around cell boundaries and the same frequency to those near base stations, has been developed so far. Ref. [4] has evaluated how the FFR increased the overall network capacity in rural environments. Our method has some similarity with those approaches in terms of cell-based resource scheduling, but most of them do not consider arbitrary, complex inter-cell interference in urban areas, and hence it is difficult to directly apply them to our case.

Network coordination is a well-known technique for spatial reuse of spectrum. For example, [5,6] organize base stations into clusters to handle them as a single network antenna array. Interference is eliminated in the clusters as clients receive the same signal from all the base stations. However, such coordination requires a large amount of effort to collect information and to synchronize the stations, which is not applicable to densely-deployed large-scale networks. In uncoordinated environment, Jindal et al. [7] have formulated the problem of determining required slots to keep high spectrum efficiency and low interference, and have analyzed the network performance with different ratios of time–frequency resources and area resources. In addition, Ref. [8] has proposed a method to adjust slots and transmission power according to spatial channel characteristics of users in a distributed manner.