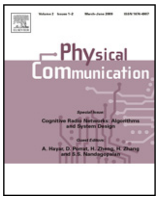
Physical Communication 12 (2014) 63–78

Contents lists available at ScienceDirect

Physical Communication

journal homepage: www.elsevier.com/locate/phycom



Full length article

Price–bandwidth dynamics for WSPs in heterogeneous wireless networks

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ARTICLE INFO

Article history:
Received 8 August 2013
Received in revised form 9 January 2014
Accepted 28 March 2014
Available online 18 April 2014

Keywords:
Heterogeneous wireless networks
Market share
Bandwidth procurement
Pricing
Spectrum sharing

ABSTRACT

This paper presents a comprehensive approach to spectrum pricing and bandwidth management for wireless service providers (WSPs) in heterogeneous wireless networks. Most approaches to spectrum management focus on revenue maximization for the WSPs. However, the key issue of the competitive edge held by a WSP over the others (i.e., its market share) is hardly addressed. The market shares of the WSPs depend on the prices they advertise and the bandwidths they provide. We develop a three phase game between WSPs. The first phase called the WSP–WSP price game enables WSPs determine the optimal price they must advertise. In the second phase, called the WSP–WSP bandwidth game, the WSPs use the Nash equilibrium of the WSP–WSP price game, to determine the optimal bandwidths they should advertise in order to maximize their market share. Finally, in the third phase, we develop a WSP–WSP trading game model the fact that users that start off with a WSP can not only demand bandwidth from that WSP, but also demand bandwidth from other WSPs in order to make best use of the available bandwidth at all the WSPs.

1. Introduction

Heterogeneous wireless networks have attained popularity because they allow mobile device connection to different access networks [1]. This flexibility was further enhanced by the advent of dynamic spectrum access (DSA) [2] based cognitive radio networks [3] provides users greater flexibility in choosing any access network belonging to any service provider. Multiple wireless service providers (WSPs) dynamically provide services to end users with varying quality-of-service (QoS) requirements over heterogeneous wireless access networks, thus providing an open market environment ("mobile-bazaar" [4]). This dynamic trading of radio spectrum brings about new challenges because service providers can set different prices and advertise different amount of bandwidths, thus creating more choices for users.

Most of the current literature on spectrum pricing and bandwidth management in heterogeneous wireless networks focus on the fairness for the users or throughput maximization or the revenue earned by the WSPs [5–9]. However, in a competitive environment, the WSPs not only desire large revenues but also wish to hold a competitive edge over the other WSPs [10]. This competitive edge is determined by the *market share*, which is defined as *the percentage of an industry or market's total sales (or revenue) that is earned by a particular firm. The market share of a firm is calculated by taking the firm's revenue over a period and dividing it by the total revenue generated by all the firms in the market, over the same period. This*

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http://dx.doi.org/10.1016/j.phycom.2014.03.001
1874-4907/

metric is used to give a general idea of the relative impact a firm has on the market, with respect to its competitors [10]. Moreover, the market share metric also is less dependent upon macro-environmental variables such as the state of the economy or changes in tax policy [10]. We therefore study management of resources and price advertisements by the WSPs so that they obtain best market share. There have been studies in economics *e.g.,* [11–13], that have emphasized on market share as the objective than just the revenues. These include applications like airline strategies [11], or incentive-based market shares [12] and more recently, for motion pictures [13]. However, to the best of our knowledge, a comprehensive study on heterogeneous wireless network environments that addresses the pricing policies and resource allocation to maximize the market shares of the WSPs has not been done yet.

This paper presents such an attempt to study the market share maximization for WSPs in heterogeneous wireless networks. The market share of the WSPs depends on their revenues, which, in turn, depends on the amount of bandwidth available at the WSPs and the price per unit bandwidth set by the WSPs. Hence, the objective of the WSPs is to advertise the right price per unit bandwidth as well as the right amount of bandwidth, which will result in a revenue that maximizes their market share. These objectives are achieved in two phases.

(i) First, the WSPs set the price per unit bandwidth that maximizes their determining the optimal revenues which provide the best profit margins for the WSPs while not losing out customers (or users) to other WSPs. This is achieved by formulating a non-cooperative *WSP–WSP price game*, whose Nash equilibrium provides the required optimal prices.
(ii) In the second phase, WSPs make use of the optimal price per unit bandwidth given by the Nash equilibrium of the WSP–WSP price game, to determine the optimal bandwidth that they must advertise, in order to yield the best market share. A non-cooperative *WSP–WSP bandwidth game* is developed to achieve this, whose Nash equilibrium yields the required solution. At this stage, the inter-dependency between the Nash equilibrium of the WSP–WSP price game and that of the WSP–WSP bandwidth game, is also established.

Finally, we discuss a third phase which accounts for the fact that users who choose a particular WSP to begin with, may later decide to either continue staying with the same WSP or move to another WSP depending on the experienced congestion and on the price advantages they obtain. We determine the optimal amount of bandwidth expended by WSPs for users who continue to stay and that for the users who move from other WSPs, by developing a non-cooperative *WSP–WSP trading game*.

The rest of the paper is organized as follows. The current related literature is presented in Section 2. Section 3 describes problem definition, the non-cooperative games between the WSPs to advertise the prices and bandwidth and to determine the amount of bandwidth expended on users that stay with and those that move from other WSPs. Sections 4 and 5 provide the numerical results and conclusions, respectively.

2. Related work

Spectrum trading and pricing in heterogeneous wireless networks has been researched widely, e.g., [5–9]. Pricing was introduced to control the selfish behavior of users and preventing from hoarding resources [5]. Huang and Mang [6] present a bandwidth management and disposition method using an upgrade and downgrade rank for users depending on their requests and the bandwidth they actually obtain. Bandwidth reservation using multiple classes of utility functions for multiple traffic classes was proposed in [8]. Bandwidth reservation for multiple classes of traffic with varying quality-of-service (QoS) requirements was studied in [7]. A fairness index based on the moment of skewness of the throughputs was studied and bandwidth was allocated to maximize the fairness index. In both the approaches mentioned above, users requesting low priority classes of traffic were starved off bandwidth to allocate bandwidth to those requesting traffic of higher priority class.

Networks with service providers have typically been analyzed from the service providers' perspective to determine the optimal pricing policies. In such competitive markets, the presence of multiple players (internet service providers (ISPs) or wireless service providers (WSPs)) results in an inter-dependence between the strategies of the players. As an example, Shakkottai and Srikant [14] demonstrated a price war between multiple internet service providers. This inter-dependence motivated the study of game theoretic models for resource allocation (e.g., [15–17]) and to determine the pricing policies (*e.g.,* [18–30] and the references therein).

A two-tier non-cooperative game theoretic auction model for differentiated services on the Internet, was presented in [18]. In [19], Yaiche et al. present a Nash bargaining solution in a cooperative game, that maximizes the revenue for the network in the presence of elastic traffic demands from the users. A Nash bargaining spectrum pricing solution for determining the optimal relay-transmitter pair in power constrained wireless networks was presented in [20]. Altman et al. [21] formulated a Stackelberg game between a service provider and users with differentiated services. In [22], Furuhata et al. proposed a game among competing retailers and studied the impact of the game with respect to the allocation strategies applied between retailers and suppliers.

Further studies on price and bandwidth competition can be found in [23–29]. Jia and Zhang [23] proposed a non-cooperative game with complete information among the WSPs to model the price and bandwidth competition. Rouskas et al. [24] developed an extensive form game to maximize the revenue of the service providers as well as model the satisfaction of the current and future users and the reputation of the service providers. Niyato et al. present an auction model for network selection in IEEE 802.22 based DSA networks in [25]. The pay off for each user depends on the frame error rate driven QoS requirements. Zhang and Zhang [26] proposed a cooperative game among the secondary users acting