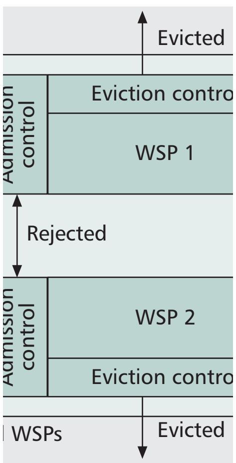
UNDERSTANDING WI-FI 2.0: FROM THE ECONOMICAL PERSPECTIVE OF WIRELESS SERVICE PROVIDERS

HYOIL KIM AND KANG G. SHIN, UNIVERSITY OF MICHIGAN



The authors focus on the economical perspective of Wi-Fi 2.0 and discuss various aspects in profit management of the Wi-Fi 2.0 WSPs. In particular, they consider profit-maximizing optimal strategies in terms of customer admission/eviction control and inter-WSP market competition.

ABSTRACT

Wi-Fi 2.0 refers to Wi-Fi-like Internet access operating on whitespaces in the licensed spectrum using cognitive radio technology. Wi-Fi 2.0 is expected to provide better performance and larger coverage than today's Wi-Fi, thanks to the good propagation characteristics of the legacy spectrum such as TV bands. Wi-Fi 2.0 is modeled as a network consisting of an access point (called CR hotspot) and end-user terminals (CR devices) operated by a CR wireless service provider. In this article we focus on the economical perspective of Wi-Fi 2.0 and discuss various aspects in profit management of Wi-Fi 2.0 WSPs. In particular, we consider profit-maximizing optimal strategies in terms of customer admission/eviction control and inter-WSP market competition. We first show that Wi-Fi 2.0 operates on time-varying spectrum availability due to the ON-OFF channel usage of legacy users, and advocate the necessity of customer eviction control upon appearance of legacy users. We also identify two types of WSP-WSP market competition in leasing the limited spectrum resources from the licensees and in enticing end customers with a competitive price. Then we enumerate the key factors affecting the profit of collocated WSPs, such as channel leasing cost, service tariff, QoS provisioning, and coexistence with legacy services. By examining Wi-Fi 2.0 from an economic point of view, we show its commercial value in developing next-generation CR applications that benefit both legacy and CR users.

INTRODUCTION

Dynamic spectrum access (DSA) paves a new way to solve the spectrum-scarcity problem caused by conventional *command-and-control* spectrum allocation. DSA enhances the efficiency in spectrum utilization of the legacy spectrum by allowing unlicensed *secondary* users (SUs) to opportunistically utilize the *whitespaces* (WS) in the licensed spectrum, which are temporarily left unused by licensed *primary* users (PUs). Such an approach has been made possible by the advent of cognitive radio (CR) technology, which enables adaptation to and awareness of time-varying wireless environments.

In 2008 the FCC released a new ruling on the allowance of the unlicensed access to the TV WS using fixed and personal/portable devices [1]. According to [1], the fixed devices may operate at up to 4 W of power, making them suitable for use in rural areas with large coverage. One example of such usage is found in IEEE 802.22, Wireless Regional Area Network (WRAN), the first international DSA standard designed for the last-mile access in rural areas. On the other hand, the personal/portable devices can operate at up to 100 mW of power targeting urban areas, which opens up the possibility of providing the Wi-Fi-like Internet access on the WS, often referred to as *Wi-Fi 2.0* [2]. Wi-Fi 2.0 is considered as a next-generation framework to enhance today's Wi-Fi by providing much higher speed and larger coverage, thanks to better propagation characteristics of the WS (e.g., TV bands) than in the industrial, scientific, and medical (ISM) bands [3].

Wi-Fi 2.0 can be modeled as a network consisting of a CR-enabled access point (called *CR hotspot*) and multiple associated CR devices as end terminals, akin to traditional Wi-Fi hotspots. Each CR hotspot is owned by a CR wireless service provider (WSP) who opportunistically utilizes the licensed spectrum to provide Internet access to the CR customers. Similar to Wi-Fi hotspots, Wi-Fi 2.0 can offer wireless services at popular public sites like coffee shops, stadiums, libraries, and airports.

THE SCOPE OF THE ARTICLE

The idea of Wi-Fi 2.0 is still in its infancy and has been discussed in the literature only in a limited form. For example, the potential of WS for enhancing Wi-Fi has been identified in [3, 4] (e.g., its ability to create a network through building walls). In [2], Deb *et al*. proposed design rules and the architecture of Wi-Fi 2.0. Bahl *et al*. [5] also proposed WhiteFi, the first Wi-Fi-like system operating on TV WS.

In this article we focus on the economic

1536-1284/10/$25.00

We envision Wi-Fi 2.0 as a realization of private commons, in the form of the three-tier dynamic spectrum market (DSM). The DSM consists of three interacting network entities: a spectrum broker, wireless service providers, and end-customers equipped with CR devices.

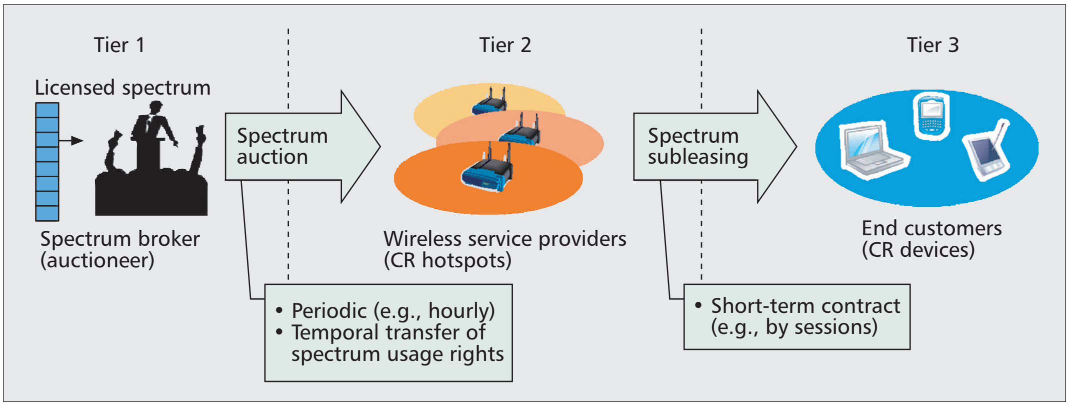


Figure 1. *The Wi-Fi 2.0 model in terms of the DSM.*

aspects of Wi-Fi 2.0 and propose possible service models and profit management schemes for CR WSPs. Identifying the economic value of Wi-Fi 2.0 is of significant importance to the integration of DSA into the legacy spectrum by providing a strong motivation to adopt CR technology and to create new CR markets and applications. Specifically, we address the mechanisms necessary for profit maximization of WSPs who charge end customers for their service, with which the WSPs can develop an efficient strategy to utilize the leased spectrum for enticing more customers.

We first identify a single WSP's optimal resource allocation strategy in terms of user admission and eviction policies. The admission policy decides whether to admit or reject a certain newly arriving user, which is one of the classical subjects in network-based market models. The eviction policy, however, is a new type of control essential for Wi-Fi 2.0 that determines which of in-service users to evict from the network at the appearance of PUs (who own higher priority in channel access) in a licensed channel. If each evicted user is compensated with partial reimbursement, the optimal choice of customers to evict becomes an important factor in the WSP's profit maximization.

We also consider two types of competition between collocated WSPs, in spectrum leasing from the licensees and in customer enticement at CR hotspots. In particular, we identify the key factors affecting their profit such as channel leasing cost, service tariff, customer satisfaction and quality of service (QoS), and coexistence with the legacy services.

Wi-Fi 2.0 Network Model

In this section we first introduce DSA spectrum sharing models and describe the architecture of Wi-Fi 2.0 in the context of such models.

DSA Spectrum-Sharing Models

DSA has introduced new spectrum-sharing models, such as *dynamic exclusive use*, *shared use*, and *private commons* [6], to achieve better efficiency in spectrum utilization. In the dynamic exclusive use model a licensee can temporarily transfer its spectrum usage rights to CR users (called *spectrum leasing*) via the *secondary market*, but the service to be used by the CR users is still restricted to the same type as the licensee. Next, in the shared use model CR users can freely access WS without any grants from the licensees as long as they do not cause any harmful interference. Lastly, the private commons model enables more flexible integration of CR devices into the licensed bands based on *real-time* spectrum leasing at the discretion of licensees who can set their own rules on how their spectrum is used by CR users.

Among the three models, the private commons model is believed to be a viable market option that benefits both licensees and CR users [6], since the licensees can make extra profit via spectrum leasing, and the CR users are given full flexibility in utilizing the WS. Unlike private commons, dynamic exclusive use regulates the type of service for opportunistic access and does not support real-time spectrum leasing. Moreover, shared use does not provide any monetary reward to the licensees for the risk of harmful interference from CR users.

We envision Wi-Fi 2.0 as a realization of private commons, in the form of the three-tier *dynamic spectrum market* (DSM) shown in Fig. 1. The DSM consists of three interacting network entities: a *spectrum broker* (SB), *wireless service providers* (WSPs), and *end customers* equipped with CR devices. In the DSM, the licensed spectrum is *periodically* auctioned off by the SB, which is either the regulatory authorities (e.g., FCC and Ofcom) or an authorized third party. The WSPs bid for the auctioned items (i.e., spectrum bands), and the winning bidder of each item is given a temporal right to reuse the leased channel until the current leasing term expires. Each WSP operates its own CR hotspots by utilizing its leased channels, and charges the end customers (i.e., CR devices) a service fee for Wi-Fi-like Internet access.

Preemptible Spectrum Leasing

We model a channel (or spectrum band) as an ON/OFF alternating source [7, 8], where an ON (or OFF) period represents the duration with (or without) PUs' signal activities. Hence, spectrum opportunities are considered to reside in the OFF periods. The transitions between ON and OFF states are detected by spectrum sensing, which is not the focus of this article (we thus assume a proper sensing mechanism is provided).

Given such a channel model, we consider *preemptible spectrum leasing* [9] as an efficient spectrum sharing mechanism between PUs and SUs, which is one possible realization of the private commons. In this model the licensees temporarily lease their channels to SUs via the periodic spectrum auction and generate additional revenue by charging the SUs for opportunistic use. The SUs are allowed to use the leased channels *only* when they are temporarily unoccupied by the PUs (i.e., the PUs are given priority over the SUs). In other words, the PUs can *preempt* SUs' opportunistic channel usage during ON periods.

TECHNICAL CHALLENGES IN WI-FI 2.0

In Wi-Fi 2.0 networks, we face new (previously unseen) challenges due to the PUs' channel usage patterns and the market competition between WSPs. In this section we briefly introduce such challenges, which are detailed later.

TIME-VARYING SPECTRUM RESOURCES

In the preemptible spectrum leasing model, the amount of leased spectrum available for use varies with time due to the ON-OFF channel patterns. For example, with M leased channels assuming homogeneous channel capacity of C, the WSP's instantaneous capacity becomes $m \cdot C$ where $m \in [0,M]$ is the number of idle channels (i.e., channels in their OFF states) at the moment. Hence, the leased channels can be considered as one *logical channel* with time-varying capacity $m \cdot C$ bandwidth units, as shown in Fig. 2.

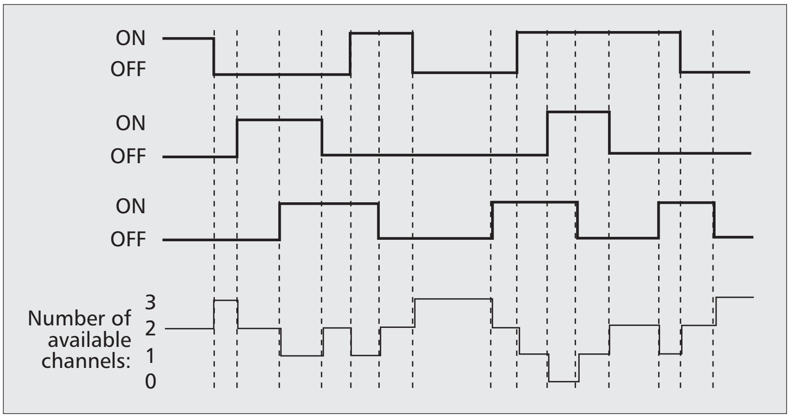


Figure 2. *Preemptible spectrum leasing: when there are three leased channels.*

The time-varying spectrum resources introduce a new challenge to the WSP. When a leased channel is idle, the channel can be assigned to the CR users admitted to the service. Unlike in the traditional Wi-Fi service, however, the channel may become busy upon the PUs' return to it. In such a case, the customers previously assigned to the channel must be relocated to other idle channels, called *channel vacation*. However, it is possible that the remaining idle channels may not be able to support the total spectrum demands of the in-service customers, and the WSP must then make one of the following two choices. First, it may degrade QoS of the in-service customers so that the total spectrum demands may be reduced to fit the remaining idle channels. Second, the WSP may perform *customer eviction*, which expels a certain number of customers from the service so that the surviving customers may still receive full service.

Eviction control is a new requirement for Wi-Fi 2.0 to determine which in-service customers to evict upon appearance of PUs. If the evicted customers are compensated for the premature termination of their service with a partial reimbursement of their service charge, an optimal eviction control becomes necessary for the management of WSPs' profit while achieving a certain level of customer satisfaction. The next section details the issue of eviction control.

PROFIT MANAGEMENT: AUCTION VS. SERVICE

To maximize a WSP's profit, two types of market competition need to be considered between collocated WSPs: channel leasing competition at the periodic auction and customer enticement competition at the CR hotspots. In the auction market a WSP has to pay the channel leasing cost to the licensees for the channels it won through the bidding process. The leasing cost function is often assumed to be non-decreasing with the number of the leased channels (i.e., M) [10], since the winning bid should increase faster than proportionally to M when WSPs are competing for limited spectrum resources. This implies that a WSP should not lease more than required to avoid exponential increase of leasing cost for spare channels.

In the CR hotspots we can consider a multi-class service where customers are grouped into one of K QoS classes. In such a model a class-k CR customer has a spectrum demand of B_k unit-bandwidth and pays a service fee of p_k per unit-time per unit-bandwidth. Then the service tariff must be carefully determined by considering a price-dependent arrival rate, $\lambda_k(p_k)$, which is non-increasing with p_k because customers are likely to choose a WSP offering a lower price.

In summary, each WSP deals with the cost incurred by channel leasing and the revenue coming from end customers. Since both factors depend on the degree of competition between the collocated WSPs, profit maximization should model such interactions by using a proper method such as game theory. The issues related to the market competition are discussed further in a later section.

USER FLOW CONTROL: SINGLE WSP'S PERSPECTIVE

The profit maximization at a CR hotspot poses a unique challenge due to the time-varying channel availability that necessitates joint user admission and eviction control. The admission control determines whether a class k customer should be admitted to the system on its arrival, and the eviction control determines which in-service users should be evicted from the system to fit the currently available spectrum resource.

The optimal user flow control strategy at a WSP can be derived for any given tariff by modeling the system as a semi-markov decision process (SMDP). The SMDP is a useful tool when we have stochastic network events and control epochs such as Poisson user arrivals/departures

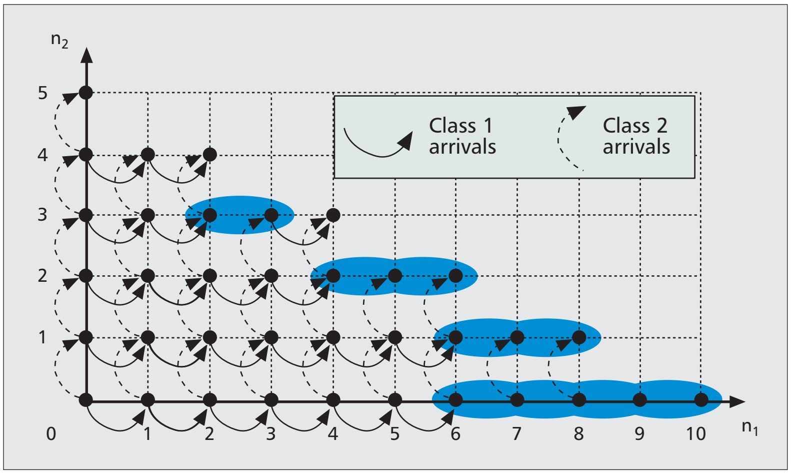


Figure 3. *The state transition diagram of optimal user control, according to the customer arrivals (when there are two idle channels).*

and exponential ON/OFF periods. In the SMDP an action is taken at each decision epoch, which is either at arrival or departure of a customer or at a channel's state transition between ON and OFF states.

The SMDP problem is formulated by defining its system state and possible actions. First, the system state can be defined as

$$\mathbf{s} = (\mathbf{n}, \mathbf{w}), \begin{cases} \mathbf{n} = (n_1, n_2, \ldots, n_K)^T \\ \mathbf{w} = (w_1, w_2, \ldots, w_M)^T \end{cases},$$

where n_k is the number of in-service class k customers and $w_i \in \{0, 1\}$ is the channel state (0/1 implies OFF/ON). In addition, the action for admission and eviction control can be defined as

$$\boldsymbol{\alpha} = (\mathbf{a}, \mathbf{b}), \begin{cases} \mathbf{a} = (a_1, a_2, \ldots, a_K)^T \\ \mathbf{b} = (b_1, b_2, \ldots, b_K)^T \end{cases},$$

where $a_k \in \{0, 1\}$ is the admission policy for future class k customer arrivals (0/1 means reject/admit) and b_k is the number of class k in-service customers to be evicted at the time of channel vacation.

When an action $\boldsymbol{\alpha}$ is taken at state $\mathbf{s}$, the profit is given as $\{r_{\mathbf{s}}(\boldsymbol{\alpha}) - c_{\mathbf{s}}(\boldsymbol{\alpha})\}$, where $r_{\mathbf{s}}(\boldsymbol{\alpha})$ denotes the expected revenue generated by the service charges on the customers, and $c_{\mathbf{s}}(\boldsymbol{\alpha})$ denotes the expected reimbursement cost paid to the evicted customers, both measured between two consecutive decision epochs. Here, the revenue is a collection of service charges from all in-service customers, where each customer pays $p_k B_k$ per unit-time. In addition, the reimbursement cost is a collection of reimbursement given to each evicted customer.

Then, an optimal action for each state can be determined to maximize the average profit of a WSP, by analyzing the SMDP using one of the three possible methods: policy iteration, value iteration, and linear programming (LP) [11]. In particular, the LP-based method is very useful to derive the optimal actions under QoS constraints by including additional equality and inequality conditions. For example, two QoS constraints can be considered: the probability of blocking class k arrivals (P_b^k) via rejection control, and the probability of dropping class k in-service customers (P_d^k) via eviction control. LP formation with such QoS constraints was introduced in [9].

Figure 3 illustrates an example of the optimal admission policy derived for a sample scenario with three leased channels (each with capacity $C = 5$) and two customer classes where $(B_1, B_2) = (1, 2)$. It can be seen that when there are two idle channels, certain arrivals are deliberately rejected (shaded regions) even if there is room. Moreover, the rejection patterns differ from the well-known threshold-type behavior that has been found optimal in the traditional network having time-invariant spectrum availability.

Tradeoff between QoS Constraints

In general, there is a trade-off between P_b^k and P_d^k: for a given number of leased channels, one should sacrifice one of the two QoS metrics to enhance the other. For example, when rejecting fewer arrivals (i.e., smaller P_b^k), a WSP should evict more customers at channel vacation due to the higher population in the service. On the contrary, when admitting fewer customers (i.e., larger P_b^k), the WSP can evict fewer customers due to the smaller spectrum demands. Therefore, to enhance both QoS metrics, one should lease more channels at the cost of a higher channel leasing price. This introduces a possibility of extending the user control problem to the context of WSP-WSP competition, which is still an open issue.

Prioritized User Control

A WSP may need to provide a prioritized service where different priority is given to user classes. In such a scenario an arriving customer can forcefully evict lower-priority in-service users to make room for the new customer. On the other hand, channel vacation evicts lower-priority in-service customers first to guarantee better service quality for higher-priority users.

This type of service will enhance today's Wi-Fi service such that customers with less critical tasks (e.g., web surfing) are grouped into a low-priority class while customers with mission-critical or spectrum-demanding tasks (e.g., video streaming) are grouped into a high-priority class. Moreover, WSPs can offer multiple price levels (e.g., gold, silver, and bronze) so that customers in the higher price group can be given higher priority and better QoS guarantees.

Market Competition: The Collocated WSPs' Perspective

The previous section has shown how a certain WSP can maximize its profit via optimal user flow control if other factors in the market are given a priori. However, in the presence of collocated WSPs, the profit maximization problem becomes more complex due to their interactions. Specifically, the price and QoS strategies of a WSP will determine how many customers it can entice (in competition with other WSPs) to enhance its profit.

It is expected that the Wi-Fi 2.0 market may experience more competition than traditional services for several reasons. First, due to the large coverage of Wi-Fi 2.0 APs, there will be more collocated WSPs creating a more competitive environment. Second, thanks to the flexible design of CR devices, CR customers are able to dynamically choose whatever wireless services are available, thus making the WSP-customer relationship volatile. This implies that CR WSPs compete not only with each other, but also with legacy services like Wi-Fi, WiMAX, and third-/fourth -generation (3G/4G) networks.

In this section, we identify and discuss the key factors contributing to the degree of market competition between collocated WSPs, including channel leasing cost, service tariff, QoS provisioning, and PU-SU coexistence.

Channel Leasing Cost

In the auction market, collocated WSPs compete for a limited amount of spectrum bands to lease. Such market competition has been modeled well by the following channel leasing cost function [10]:

$$l = \gamma_1 (C_i + C_{-i})\gamma_2,\ \gamma_1 > 0,\ \gamma_2 \geq 1,$$

where C_i implies the amount of spectrum WSP i seeks to lease, and C_{-i} is the cumulative spectrum demand from the competitors of WSP i. Then WSP i's channel leasing cost becomes $C_i \cdot l$, while l is a function of the total spectrum demand in the auction market (i.e., $C_i + C_{-i}$). Therefore, WSP i should consider the spectrum demand from its competitors as well, which can be dealt with by game theory.

There have been numerous attempts to analyze such competition with game-theoretic approaches [10, 12, 13], all of which are limited to time-invariant spectrum availability. Therefore, an enhanced analysis is desired to incorporate a time-varying spectrum availability model in Wi-Fi 2.0 with inter-WSP dependency in spectrum leasing.

Service Tariff

One of the important factors a WSP should consider to maximize its profit is its pricing strategy. Figure 4 illustrates the relationship between collocated WSPs in terms of the price-dependent arrival rates, where class k customers arrive as a bulk at the rate of λ_k and choose their own service provider independently. According to the user preference, the arrivals are split into rates λ_k^1 and λ_k^2 such that $\lambda_k = \lambda_k^1 + \lambda_k^2$. At one extreme, either of two rates may become arbitrarily small if its WSP is offering a higher price. On the other hand, when a WSP rejects an arrival, the user may choose its competitor to receive a service. Hence, there exists a trade-off: a lower price attracts more customer arrivals while less revenue per customer is achieved; a higher price limits customer arrivals but yields higher per-customer revenue.

To show the price-profit relationship, we present an illustrative example for $M = 3$ and $K = 2$ where the service tariff for two user classes varies as $0.5 \leq p_1, p_2 \leq 3.5$. In addition, the arrival rate is assumed as $\lambda_k(p_k) = \lambda_k^{\max} e^{-p_k}$ to model the WSP-WSP price competition, where $\lambda_k^{\max}$ is the maximum customer population at a given location. Figure 5 plots the resulting profit g^* of a WSP, showing that the profit function becomes concave for two reasons:

- As p_k gets smaller, the profit decreases because the user arrival rate is upper bounded by $\lambda_k^{\max}$.
- As p_k gets larger, the profit k decreases due to the exponential decrease of user arrivals according to e^{-p_k}.

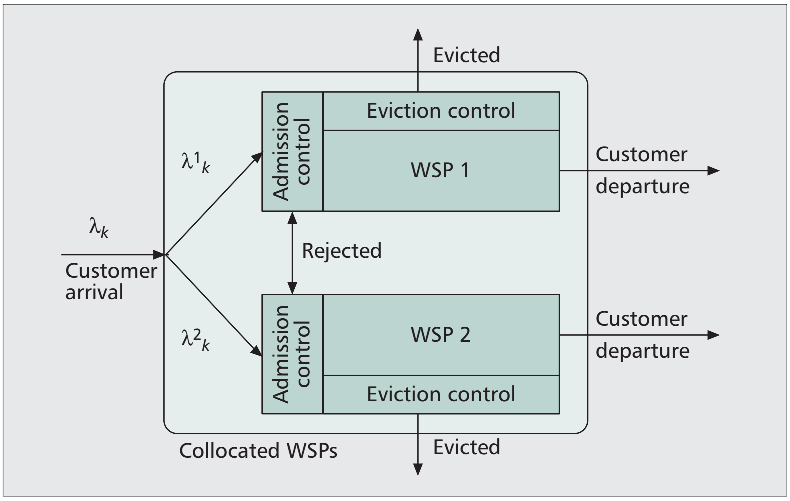


Figure 4. *The market dynamics between collocated WSPs.*

Customer Satisfaction and QoS Provisioning

The user QoS satisfaction also affects the WSP's profit, which is described in terms of several factors, such as the probability of blocking and dropping, QoS degradation, and the amount of reimbursement in case of eviction. First, smaller P_b^k and P_d^k offer better user QoS, enticing more customers. Hence, a WSP should strike a balance between its tariff and QoS provisioning since better QoS can be achieved by leasing more channels, which in turn incurs higher channel leasing cost. Second, user eviction may be replaced by QoS degradation of in-service customers, suppressing user eviction only to the case when there remains no idle channel. However, QoS degradation also affects customer satisfaction, especially of users with resource-demanding jobs, which eventually impairs the WSP's reputation. Therefore, the rate and frequency of QoS degradation must be controlled within an acceptable range that would not cause reduced customer arrivals by harming the reputation. Finally, although larger reimbursement may entice more customers, such reimbursement cannot offset the dissatisfaction of evicted customers with critical tasks. Hence, the WSP offering a more sophisticated eviction policy will have an advantage, such as differentiating job-critical users from mundane users via the prioritized control introduced earlier.

Coexistence with Legacy Services

Although collocated WSPs are competing with each other, they also need to cooperate as a team to make the Wi-Fi 2.0 market more attractive to customers than competing legacy ser-

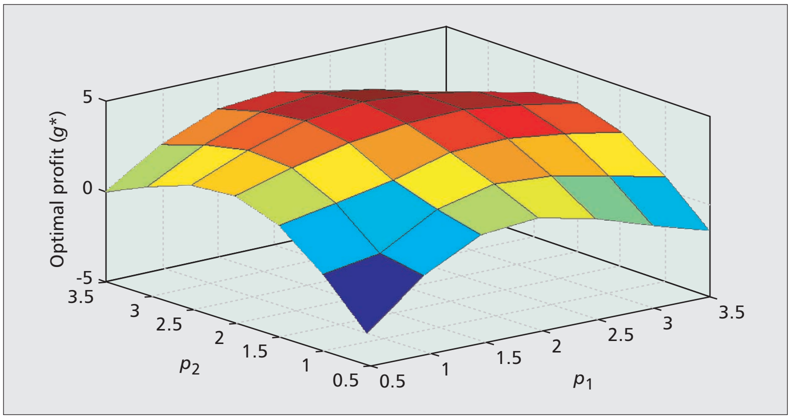


Figure 5. *Optimal profit with various end-user pricing.*

vices. This is because CR devices have agility to configure themselves as legacy terminals as well as Wi-Fi 2.0 clients, choosing the service that best serves their need. Therefore, the overall Wi-Fi 2.0 network must appeal to customers as a cheaper-but-quality service to increase the number of customers visiting the CR networks. Examples of inter-WSP cooperation include setting the price cap, forming a coalition between neighboring WSPs, and sharing spectrum sensor networks to reduce the sensing overhead. In a similar vein, Aram *et al*. [14] introduced cooperative profit sharing between WSPs collocated through multihop routes, and have shown that resource pooling of spectrum and access points can potentially increase their aggregate payoffs.

Conclusion

In this article we have discussed research challenges in the Wi-Fi 2.0 network from the CR WSPs' perspective. We first introduced an efficient and practical spectrum reuse model that benefits both PUs and SUs, and then considered the WSP's profit maximization problem in terms of the customer admission/eviction control and inter-WSP market competition. Via a comprehensive overview of Wi-Fi 2.0 from its economic point of view, the practical value of Wi-Fi 2.0 is presented to motivate active integration of DSA into the legacy spectrum.

References

[1] FCC, "Second Report and Order and Memorandum Opinion and Order," FCC 08-260, Nov. 2008.

[2] S. Deb, V. Srinivasan, and R. Maheshwari, "Dynamic Spectrum Access in DTV Whitespaces: Design Rules, Architecture, and Algorithms," *ACM MobiCom*, Sept. 2009.

[3] J.M. Chapin and W.H. Lehr, "The Path to Market Success for Dynamic Spectrum Access Technology," *IEEE Commun. Mag.*, vol. 45, no. 5, May 2007, pp. 96–103.

[4] A. Stirling, "White Spaces — The New Wi-Fi?," *Int'l. J. Digital Television*, vol. 1, no. 1, 2010, pp. 69–83.

[5] P. Bahl *et al.*, "White Space Networking with Wi-Fi like Connectivity," *ACM SIGCOMM*, Aug. 2009.

[6] M. M. Buddhikot, "Understanding Dynamic Spectrum Access: Models, Taxonomy and Challenges," *IEEE DySPAN*, Apr. 2007, pp. 649–63.

[7] S. Geirhofer, L. Tong, and B. M. Sadler, "Dynamic Spectrum Access in the Time Domain: Modeling and Exploiting White Space," *IEEE Commun. Mag.*, vol. 45, no. 5, May 2007, pp. 66–72.

[8] H. Kim and K. G. Shin, "Efficient Discovery of Spectrum Opportunities with MAC-Layer Sensing in Cognitive Radio Networks," *IEEE Trans. Mobile Comp.*, vol. 7, no. 5, May 2008, pp. 533–45.

[9] H. Kim and K. G. Shin, "Optimal Admission and Eviction Control of Secondary Users at Cognitive Radio HotSpots," *IEEE SECON*, June 2009.

[10] J. Jia and Q. Zhang, "Competitions and Dynamics of Duopoly Wireless Service Providers in Dynamic Spectrum Market," *ACM MobiHoc*, May 2008, pp. 313–22.

[11] H.C. Tijms, *Stochastic Modelling and Analysis: A Computational Approach*, Wiley, 1986.

[12] L. Duan, J. Huang, and B. Shou, "Competition with Dynamic Spectrum Leasing," *IEEE DySPAN*, Apr. 2010.

[13] G. S. Kasbekar, E. Altman, and S. Sarkar, "A Hierarchical Spatial Game over Licenced Resources," *GameNets*, June 2009, pp. 70–79.

[14] A. Aram *et al.*, "Cooperative Profit Sharing in Coalition Based Resource Allocation in Wireless Networks," *IEEE INFOCOM*, Apr. 2009, pp. 1–11.

Biographies

HYOIL KIM [S '09] (hyoilkim@eecs.umich.edu) is a Ph.D. candidate in the Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor. He received his B.S. degree in electrical engineering from Seoul National University, Korea in 1999, and his M.S. degree from the University of Michigan in 2005. Since 2004 he has been a research assistant at the Real-Time Computing Laboratory in the EECS Department, The University of Michigan. His research interests include CRs and DSA, with an emphasis on network optimization, spectrum sensing, spectrum resource management, QoS, and dynamic spectrum market mechanisms. He has been awarded the Korea Science and Engineering Foundation (KOSEF) Scholarship in 2003–2005 and the Samsung Scholarship in 2005–2009. He serves as a peer reviewer for many IEEE journals and conferences.

KANG G. SHIN [F '92] (kgshin@eecs.umich.edu) is the Kevin and Nancy O'Connor Professor of Computer Science and founding director of the Real-Time Computing Laboratory in the Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor. His current research focuses on computing systems and networks as well as on embedded real-time and cyber-physical systems, all with emphasis on timeliness, security, and dependability. He has supervised the completion of 65 Ph.D.s, and authored/coauthored more than 720 technical articles. He has co-authored (with C. M. Krishna) a textbook, *Real-Time Systems* (McGraw Hill, 1997). He has received numerous best paper awards, including the Best Paper at the 2010 USENIX Annual Technical Conference, the IEEE Communications Society William R. Bennett Prize Paper Award in 2003, the Best Paper Award from IWQoS '03 in 2003, and an Outstanding *IEEE Transactions of Automatic Control* Paper Award in 1987. He has also coauthored papers with his students, which received the Best Student Paper Awards from the 1996 IEEE Real-Time Technology and Application Symposium and the 2000 UNSENIX Technical Conference. He has also received several institutional awards, including the Research Excellence Award in 1989, Outstanding Achievement Award in 1999, Service Excellence Award in 2000, Distinguished Faculty Achievement Award in 2001, and Stephen Attwood Award in 2004 from The University of Michigan (the highest honor bestowed to Michigan Engineering faculty); a Distinguished Alumni Award of the College of Engineering, Seoul National University in 2002; 2003 IEEE RTC Technical Achievement Award; and 2006 Ho-Am Prize in Engineering (the highest honor bestowed to Korean-origin engineers). He is a Fellow of ACM and has chaired numerous conferences, including the 2009 ACM MobiCom '09, IEEE SECON '08, ACM/USENIX MobiSys '05, and IEEE RTAS 2000, and IEEE RTSS '86 and '87. He also chaired the IEEE Technical Committee on Real-Time Systems, 1991–1993, and has served as an Editor of *IEEE Transactions on Parallel and Distributed Computing*, and an Area Editor of the *International Journal of Time-Critical Computing Systems*, *Computer Networks* and *ACM Transactions on Embedded Systems*