On Optimal Admission Control for Multi-Service Cellular/WLAN Interworking

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Abstract— **The complementary characteristics of cellular systems and wireless local area networks (WLANs) make them attractive candidates to jointly offer a seamless wireless solution. In an integrated cellular/WLAN system, the quality of service (QoS) requirements for different services (e.g., voice and real-time video) require adequate admission control policies to limit the number of connections in each network. In this paper, we analytically develop a comprehensive model to facilitate the optimal evaluation of different admission control policies in a multi-service integrated cellular/WLAN system. Given the model, we formulate two optimization problems to adjust admission control parameters. The first problem is to maximize the network revenue while the second problem is to minimize the required network resources subject to QoS constraints. We evaluate each problem when different combinations of cutoff priority and fractional guard channel admission control policies are being used. We show that a combination of two cutoff priority policies achieves the best solution for both problems.**

I. Introduction

Recent studies show that wireless wide area networks, such as cellular systems, can be integrated with wireless local area networks (WLANs) to offer Internet and multimedia services to mobile users [1]. In an integrated cellular/WLAN system, mobile devices are equipped with multiple interfaces to establish connections with different networks. As the users move within the coverage areas, they are able to switch connections among networks according to roaming agreements. Some vendors have begun to offer products in this area. The IEEE has also set up the 802.21 working group to standardize inter-operability between 802 and non-802 networks [2].

The process of switching connections among networks is called *handoff*. A handoff is *horizontal* if it is between networks using the same access technology (e.g., two WLANs). It is *vertical* if it is between networks using different access technologies (e.g., from cellular to a WLAN). To guarantee the quality of service (QoS) for different multimedia applications, it is necessary to limit the number of connections in both wireless networks. In each network, an *admission control policy* either accepts the connection request and accordingly allocates the requested bandwidth or blocks the connection request. Higher priority is usually given to accept the connection requests from *handoff users* (as opposed to the *new users*). The reason is that from the user's viewpoint, having a connection abruptly terminated is more annoying than being blocked occasionally on new connection attempts.

Some of the well-known admission control policies from cellular networks include *cutoff priority* (CP) [3] and *fractional guard channel* (FG) [4]. The CP policy reserves a fixed number of channels to *exclusively* accept connection requests from handoff users. The connection requests from new users are blocked if there is no unreserved channel available. The FG policy reserves channels for handoff requests by blocking the connection requests from new users with some *probability* proportional to the current *channel occupancy*. Admission control for multi-service cellular networks has been investigated in [5]–[7]. In some cases, the design goal is to maximize the network revenue [6], [7], while some others try to minimize the required network resources subject to QoS guarantees [4].

Similar objectives can be considered in designing optimal admission control policies for integrated cellular/WLAN systems. For single-service cellular/WLAN, the new call bounding policy is used in [8]. A randomized FG policy is considered in [9] to maximize the network revenue in an integrated voice/data cellular/WLAN. A modified FG is also proposed in [10] to manage network resources for voice connections. In [11], vertical handoffs are used for admission control to jointly use network radio resources. However, there is no study to examine the capability of different combinations of admission control policies under both design goals, i.e., maximizing network revenue and minimizing required network resources.

In this paper, we develop a general model to facilitate the optimal evaluation of different admission control policies in a multi-service integrated cellular/WLAN system. The contributions of our work are as follows:

- Our model takes into account the mobility and traffic patterns, the capacity and coverage area of each network, admission control policies, and QoS requirements.
- We formulate network revenue maximization as well as required resource minimization problems for multi-service cellular/WLAN interworking.
- We evaluate the capability of reaching the global optimums of each problem using different combinations of CP and FG policies. We show that a combination of two CP policies achieves the best solution for both problems.

The rest of the paper is organized as follows. The model for the integrated cellular/WLAN system is described in Section II. Optimization-based admission control problems are formulated in Section III. Numerical results are presented in Section IV. Conclusions are given in Section V.

II. Cellular/WLAN System Model

Consider an integrated cellular/WLAN system where one or more WLANs may be deployed inside each cell of the cellular system as shown in Fig. 1. There are two specific coverage areas to be considered: the *cellular-only coverage area*, and the *dual cellular/WLAN coverage area*. In this context, coverage means service availability. Horizontal and vertical handoffs can occur in different coverage areas. In this section, we describe the model to formulate a multi-service integrated cellular/WLAN system. Given the admission control policies, we determine blocking probabilities for new and handoff users.

A. Traffic and Mobility Models

Let M^c denote the set of all cells. Also let A_i^c denote the set of cells adjacent to cell i, W_i^c denote the set of WLANs inside the coverage area of cell i, A_k^w denote the set of WLANs adjacent to WLAN k, and D_k^w denote the set containing the overlaying cell of WLAN k (i.e., a dual cellular/WLAN coverage area). As an example, from Fig. 1, we have: $M^c = \{1,2,3,4\}$, $A_1^c = \{2,3,4\}$, $W_1^c = \{5,6\}$, $A_5^w = \{6\}$, and $D_5^w = \{1\}$. Let S denote the set of all multimedia services. Each service $s \in S$ requires b_s basic bandwidth units (BBU) [5] or channels to fully satisfy its QoS requirements. The new connection requests for service s arrive at cell i and WLAN k according to independent Poisson processes with rates $\lambda_{i_s}^c$ and $\lambda_{k_s}^w$, respectively. The duration of each connection of service s is defined as *connection time* t_s. We assume that t_s is an exponentially distributed random variable with mean $1/\upsilon_s$. Because of the memoryless property of exponential distribution, the residual (i.e., remaining) connection time t_s^R is also exponentially distributed with mean $1/\upsilon_s$.

To model the mobility, we define *inter-boundary time*, similar to [12], as the time interval between any two consecutive access network boundary crossings by a mobile user. The wider the coverage areas or the more stationary the users, the longer the inter-boundary times are. If an inter-boundary time starts at the moment of entering cell i, then we denote it by $t_{b_i}^c$. If an inter-boundary time starts at the moment of entering WLAN k, then we denote it by $t_{b_k}^w$. We assume that $t_{b_i}^c$ and $t_{b_k}^w$ are exponentially distributed with means $1/\eta_i^c$ and $1/\eta_k^w$, respectively. Fig. 1 shows $t_{b_i}^c$ between boundary crossing points A and B, and $t_{b_k}^w$ between points B and C.

We now define the *channel holding time* as the time that a connected mobile user keeps using BBU resources in each network. For service s, the channel holding times in cell i and in WLAN k are obtained as $\min(t_s^R, t_{b_i}^c)$ and $\min(t_s^R, t_{b_k}^w)$, respectively. Since t_s^R, $t_{b_i}^c$, and $t_{b_k}^w$ have exponential distributions for all $s \in S$, $i \in M^c$, and $k \in W_i^c$, the channel holding times are also exponentially distributed with parameters $\mu_{i_s}^c = \upsilon_s + \eta_i^c$ and $\mu_{k_s}^w = \upsilon_s + \eta_k^w$, respectively.

A mobile user who is holding a connection of service s in cell i may terminate its connection at the end of its holding time and leave the cellular/WLAN system with probability $q_{i_s}^c = \upsilon_s/(\upsilon_s + \eta_i^c)$. It may also move within the system and continue in an adjacent cell or an underlaying WLAN with probability $1 - q_{i_s}^c$. We have:

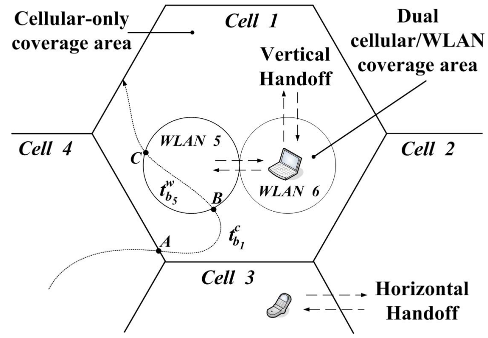

Fig. 1. An integrated multi-service cellular/WLAN system.

$$1 - q_{i_s}^c = \frac{\eta_i^c}{\upsilon_s + \eta_i^c} = \sum_{j \in A_i^c} q_{ij_s}^{cc} + \sum_{k \in W_i^c} q_{ik_s}^{cw}, \tag{1}$$

where $q_{ij_s}^{cc}$ denotes the probability of attempting a horizontal handoff from cell i to adjacent cell j, and $q_{ik_s}^{cw}$ denotes the probability of attempting a vertical handoff from cell i to WLAN k inside cell i.

On the other hand, a mobile user who is holding a connection of service s in WLAN k may terminate its connection at the end of its holding time and leave the cellular/WLAN system with probability $q_{k_s}^w = \upsilon_s/(\upsilon_s + \eta_k^w)$. It may also move within the system and continue in an adjacent WLAN or an overlaying cell with probability $1 - q_{k_s}^w$. We have:

$$1 - q_{k_s}^w = \frac{\eta_k^w}{\upsilon_s + \eta_k^w} = \sum_{l \in A_k^w} q_{kl_s}^{ww} + \sum_{i \in D_k^w} q_{ki_s}^{wc}, \tag{2}$$

where $q_{kl_s}^{ww}$ denotes the probability of attempting a horizontal handoff from WLAN k to adjacent WLAN l, and $q_{ki_s}^{wc}$ denotes the probability of attempting a vertical handoff from cell k to its overlaying cell i.

B. Multi-Dimensional Birth-Death Processes

Each cell i of the cellular system is assumed to have a capacity of C_i^c BBUs. Let $m_{i_s}^c \geq 0$ denote the number of connections of multimedia service s in cell i. The capacity constraint requires that,

$$\sum_{s \in S} m_{i_s}^c b_s \leq C_i^c, \qquad \forall\, i \in M^c. \tag{3}$$

From (3), there can be at most $\lfloor C_i^c / b_s \rfloor$ connections of service s in cell i at any time. We define $\boldsymbol{m_i^c} = (m_{i_1}^c, m_{i_2}^c, ..., m_{i_S}^c)$ as the *channel occupancy vector* in cell i. For each cell $i \in M^c$, admission control policies on connection requests from new and handoff users for service $s \in S$ can be modeled by *policy functions* $\beta_{n_{i_s}}^c(\boldsymbol{m_i^c})$ and $\beta_{h_{i_s}}^c(\boldsymbol{m_i^c})$, respectively. Policy function $\beta_{n_{i_s}}^c(\boldsymbol{m_i^c})$ determines the probability of blocking a connection request from a new user for service s in cell i. Similarly, policy function $\beta_{h_{i_s}}^c(\boldsymbol{m_i^c})$ determines the probability of blocking a connection request from a handoff user for service s in cell i. Since the connection requests from handoff users have higher priority than the connection requests from new users. It requires that $\beta_{h_{i_s}}^c(\boldsymbol{m_i^c}) \leq \beta_{n_{i_s}}^c(\boldsymbol{m_i^c})$ for all $i \in M^c$, and $s \in S$. Many admission control policies, including CP and FG can be mathematically modeled in the form of their corresponding policy functions. We will discuss policy functions in more detail in Section III.

A channel occupancy vector $\boldsymbol{m_i^c}$ is *feasible* if $m_{i_s}^c \geq 0$ for all $s \in S$ and (3) holds. We denote the set of all feasible $\boldsymbol{m_i^c}$ as Θ_i^c. The *occupancy* of cell i evolves according to a multi-dimensional *birth-death* process [13] independent of other cells. A *birth event* happens when a connection request to cell i from a handoff or a new user is accepted. A *death event* happens when a user terminates its connection or leaves cell i. The multi-dimensional birth-death process has $|S|$ dimensions, where $|\cdot|$ denotes the set's cardinality. The s^{th} dimension models the channel occupancy evolvement because of changes in the number of connections of service s.

Let $P_i^c(m_{i_1}^c, m_{i_2}^c, ..., m_{i_S}^c)$ (or simply $P_i^c(\boldsymbol{m_i^c})$) denote the probability of being in state $(m_{i_1}^c, m_{i_2}^c, ..., m_{i_S}^c)$ in the $|S|$-dimensional birth-death process corresponding to cell i. We have,

$$B_{n_{i_s}}^c = \sum_{\boldsymbol{m_i^c} \in \Theta_i^c} P_i^c(\boldsymbol{m_i^c}) \beta_{n_{i_s}}^c(\boldsymbol{m_i^c}), \tag{4}$$

$$B_{h_{i_s}}^c = \sum_{\boldsymbol{m_i^c} \in \Theta_i^c} P_i^c(\boldsymbol{m_i^c}) \beta_{h_{i_s}}^c(\boldsymbol{m_i^c}), \tag{5}$$

where $B_{n_{i_s}}^c$ and $B_{h_{i_s}}^c$ denote the probability of blocking connection requests for service s in cell i from new and handoff users, respectively.

To model the capacity in IEEE 802.11 WLANs, we reasonably assume that there are only packet transmissions from the access points to the users and vice versa, but not among the users. For each WLAN k, the media access is controlled either in a centralized manner using the Point Coordination Function (PCF), or in a decentralized manner using the Distributed Coordination Function (DCF). We show in the Appendix that in either case, the capacity constraint can be modeled as:

$$\sum_{s \in S} m_{k_s}^w b_s \leq C_k^w, \quad \forall\, k \in W_i^c, \tag{6}$$

where C_k^w is the *nominal* data rate in WLAN k, b_s is the required effective data rate for service $s \in S$ in BBUs, and $m_{k_s}^w \geq 0$ is the number of connections of service s in WLAN k. We define $\boldsymbol{m_k^w} = (m_{k_1}^w, m_{k_2}^w, ..., m_{k_S}^w)$ as the *channel occupancy vector* in WLAN k.

Consider an arbitrary cell $i \in M^c$. For each WLAN $k \in W_i^c$, admission control policies on connection requests from handoff and new users for service $s \in S$ can be modeled by *policy functions* $\beta_{n_{k_s}}^w(\boldsymbol{m_k^w})$ and $\beta_{h_{k_s}}^w(\boldsymbol{m_k^w})$, respectively.

A channel occupancy vector $\boldsymbol{m_k^w}$ is *feasible* if $m_{k_s}^w \geq 0$ for all $s \in S$ and (6) holds. We denote the set of all feasible $\boldsymbol{m_k^w}$ as Θ_k^w. The *occupancy* of WLAN k evolves according to an $|S|$-dimensional *birth-death* process independent of other WLANs. Let $P_k^w(m_{k_1}^w, m_{k_2}^w, ..., m_{k_S}^w)$ (or simply $P_k^w(\boldsymbol{m_k^w})$) denote the probability of being in state $(m_{k_1}^w, m_{k_2}^w, ..., m_{k_S}^w)$ in the $|S|$-dimensional birth-death process corresponding to WLAN k. Let $B_{n_{k_s}}^w$ and $B_{h_{k_s}}^w$ denote the probability of blocking connection requests for service s in WLAN k for new and handoff users, respectively. We have,

$$B_{n_{k_s}}^w = \sum_{\boldsymbol{m_k^w} \in \Theta_k^w} P_k^w(\boldsymbol{m_k^w}) \beta_{n_{k_s}}^w(\boldsymbol{m_k^w}), \tag{7}$$

$$B_{h_{k_s}}^w = \sum_{\boldsymbol{m_k^w} \in \Theta_k^w} P_k^w(\boldsymbol{m_k^w}) \beta_{h_{k_s}}^w(\boldsymbol{m_k^w}). \tag{8}$$

Let $\phi_{i_s}^c$ denote the *birth rate* (i.e., the rate of occurring a birth event) of service s in the birth-death process corresponding to cell i. Similarly, let $\phi_{k_s}^w$ denote the birth rate of service s in the process corresponding to WLAN k. We have:

$$\begin{aligned} \phi_{i_s}^c = \lambda_{i_s}^c \left(1 - \beta_{n_{i_s}}^c(\boldsymbol{m_i^c})\right) + \Bigg[\sum_{j \in A_i^c} h_{ji_s}^{cc} \\ + \sum_{k \in W_i^c} v_{ki_s}^{wc} + \sum_{k \in W_i^c} \tau_{ki_s}^{wc} \Bigg] \left(1 - \beta_{h_{i_s}}^c(\boldsymbol{m_i^c})\right), \end{aligned} \tag{9}$$

$$\begin{aligned} \phi_{k_s}^w = \lambda_{k_s}^w \left(1 - \beta_{n_{k_s}}^w(\boldsymbol{m_k^w})\right) + \Bigg[\sum_{l \in A_k^w} h_{lk_s}^{ww} \\ + \sum_{i \in D_k^w} v_{ik_s}^{cw} + \sum_{i \in D_k^w} \tau_{ik_s}^{cw} \Bigg] \left(1 - \beta_{h_{k_s}}^w(\boldsymbol{m_k^w})\right), \end{aligned} \tag{10}$$

where $h_{ij_s}^{cc}$ denotes the *horizontal* handoff rate of service s offered to cell i from its adjacent cell j, $v_{ki_s}^{wc}$ denotes the *vertical* handoff rate of service s offered to cell i from its underlying WLAN k, $\tau_{ki_s}^{wc}$ denotes the rate of all handoff traffic of service s that is not accepted in WLAN k and hence is *transferred* to cell i, $h_{lk_s}^{ww}$ denotes the *horizontal* handoff rate of service s offered to WLAN k from its adjacent WLAN l, $v_{ik_s}^{cw}$ denotes the *vertical* handoff rate of service s offered to WLAN k from its overlaying cell i, and $\tau_{ik_s}^{cw}$ denotes the rate of all handoff traffic of service s that is not accepted in cell i and hence is *transferred* to WLAN k. We have:

$$\begin{aligned} h_{ji_s}^{cc} = \lambda_{j_s}^c \left(1 - B_{n_{j_s}}^c\right) q_{ji_s}^{cc} + \Bigg[\sum_{x \in A_j^c} h_{xj_s}^{cc} \\ + \sum_{l \in W_j^c} v_{lj_s}^{wc} + \sum_{l \in W_j^c} \tau_{lj_s}^{wc} \Bigg] \left(1 - B_{h_{j_s}}^c\right) q_{ji_s}^{cc}, \end{aligned} \tag{11}$$

$$\begin{aligned} v_{ki_s}^{wc} = \lambda_{k_s}^w \left(1 - B_{n_{k_s}}^w\right) q_{ki_s}^{wc} + \Bigg[\sum_{l \in A_k^w} h_{lk_s}^{ww} \\ + \sum_{j \in D_k^w} v_{jk_s}^{cw} + \sum_{j \in D_k^w} \tau_{jk_s}^{cw} \Bigg] \left(1 - B_{h_{k_s}}^w\right) q_{ki_s}^{wc}, \end{aligned} \tag{12}$$

$$\tau_{ki_s}^{wc} = v_{ik_s}^{wc} B_{h_{k_s}}^w + \sum_{l \in A_k^w} h_{lk_s}^{ww} B_{h_{k_s}}^w, \tag{13}$$

$$\begin{aligned} h_{lk_s}^{ww} = \lambda_{l_s}^w \left(1 - B_{n_{l_s}}^w\right) q_{lk_s}^{ww} + \Bigg[\sum_{y \in A_l^w} h_{yl_s}^{ww} \\ + \sum_{i \in D_l^w} v_{il_s}^{cw} + \sum_{i \in D_l^c} \tau_{il_s}^{cw} \Bigg] \left(1 - B_{h_{l_s}}^w\right) q_{lk_s}^{ww}, \end{aligned} \tag{14}$$

$$v_{ik_s}^{cw} = \lambda_{i_s}^{c}\left(1 - B_{n_{i_s}}^{c}\right) R_{ik} q_{ik_s}^{cw} + \Bigg[\sum_{j\in A_i^c} h_{ji_s}^{cc} R_{ik} + \sum_{l\in W_i^c} v_{li_s}^{wc} R_{ik} + \sum_{l\in W_i^c} \tau_{li_s}^{wc}\Bigg]\left(1 - B_{h_{i_s}}^{c}\right) q_{ik_s}^{cw}, \tag{15}$$

$$\tau_{ik_s}^{cw} = \left(v_{ki_s}^{cw} B_{h_{i_s}}^{c} + \sum_{j\in A_i^c} h_{ji_s}^{cc} B_{h_{i_s}}^{c} \right) R_{ik}, \tag{16}$$

where R_{ik} denotes the *coverage factor* between WLAN k and cell i (i.e., the ratio between the radio coverage area of WLAN k and the radio coverage area of cell i). Note that we always have $0 \le R_{ik} \le 1$ for all $i \in M^c$ and $k \in W_i^c$.

Let $\varphi_{i_s}^c$ denote the *death rate* (i.e., the rate of occurring a death event) of service s in the birth-death process corresponding to cell i. Similarly, let $\varphi_{k_s}^w$ denote the death rate of service s in the process corresponding to WLAN k. We have:

$$\varphi_{i_s}^c = m_{i_s}^c \mu_{i_s}^c, \tag{17}$$

$$\varphi_{k_s}^w = m_{k_s}^w \mu_{k_s}^w. \tag{18}$$

Given the policy functions $\beta_{n_{i_s}}^c$, $\beta_{h_{i_s}}^c$, $\beta_{n_{k_s}}^w$, and $\beta_{h_{k_s}}^w$ and network parameters $\lambda_{i_s}^c$, $\lambda_{k_s}^w$, η_i^c, η_k^w, $\mu_{i_s}^c$, $\mu_{k_s}^w$, $q_{ik_s}^{cw}$, $q_{ij_s}^{cc}$, $q_{ki_s}^{wc}$, $q_{kl_s}^{ww}$, C_i^c, C_k^w, υ_s, b_s for all $i, j \in M^c$, all $k, l \in W_i^c$, and all $s \in S$, we can solve the global balance equations from the birth-death processes and obtain blocking probabilities $B_{n_{i_s}}^c$, $B_{h_{i_s}}^c$, $B_{n_{k_s}}^w$, and $B_{h_{k_s}}^w$ for all $i \in M^c$, $k \in W_i^c$, and $s \in S$. To compute the birth rates in (9) and (10), we need to solve the set of fixed-point equations given by the handoff rates (11)-(16). It can be accomplished by using the iterative fixed-point algorithm of repeated substitutions [14].

III. Optimal Admission Control

The mathematical formulation introduced in (1)-(18) models a multi-service integrated cellular/WLAN system. The model can be used to evaluate the current admission control policies or to propose new policies. In this section, we extend CP and FG as two example admission control policies from cellular networks to be used in integrated cellular/WLAN systems. Recall that CP policy reserves a fixed number of available channels for handoff requests. Using the notation of policy functions, a connection request to cell i for service s is blocked by CP policy with the following probabilities:

$$\beta_{n_{i_s}}^c(\boldsymbol{m_i^c}) = \begin{cases} 0, & \text{if } \sum_{s'\in S} m_{i_{s'}}^c b_{s'} \le T_{i_s}^c, \\ 1, & \text{otherwise.} \end{cases} \tag{19}$$

$$\beta_{h_{i_s}}^c(\boldsymbol{m_i^c}) = \begin{cases} 0, & \text{if } \sum_{s'\in S} m_{i_{s'}}^c b_{s'} \le C_i^c - b_s, \\ 1, & \text{otherwise,} \end{cases} \tag{20}$$

where $\sum_{s'\in S} m_{i_{s'}}^c b_{s'}$ denotes the current channel occupancy, and *integer* parameter $T_{i_s}^c$ is used to tune the *threshold* to give priority to handoffs. Note that for all $i \in M^c$ and $s \in S$, we have: $0 \le T_{i_s}^c \le C_i^c - b_s$. Considering the extreme cases, if $T_{i_s}^c = C_i^c - b_s$, then there is indeed no admission control in cell i for multimedia service s. On the other hand, if $T_{i_s}^c = 0$, then all requests from new users for service s are blocked.

Unlike CP, in FG policy, requests from new users are blocked with a probability proportional to the current channel occupancy. A connection request to cell i from a new user for service s is blocked by FG with the following probability:

$$\beta_{n_{i_s}}^c(\boldsymbol{m_i^c}) = \begin{cases} 0, & \text{if } \sum_{s'\in S} m_{i_{s'}}^c b_{s'} \le T_{i_s}^c, \\ \dfrac{\sum_{s'\in S} m_{i_{s'}}^c b_{s'} - T_{i_s}^c}{C_i^c - b_s + 1 - T_{i_s}^c}, & \text{otherwise,} \end{cases} \tag{21}$$

while $\beta_{h_{i_s}}^c(\boldsymbol{m_i^c})$ is the same as (20).

For WLAN k, connection requests from new and handoff users for service s are blocked with probabilities $\beta_{n_{k_s}}^w(\boldsymbol{m_k^w})$ and $\beta_{h_{k_s}}^w(\boldsymbol{m_k^w})$, respectively. Such policy functions are defined according to CP or FG, but with the corresponding WLAN parameters C_k^w and $T_{k_s}^w$. In both networks, $T_{i_s}^c$ and $T_{k_s}^w$ are the admission control parameters to be optimized.

In general, four different combinations can be considered:

1) Cellular systems and WLANs use CP (CP^c-CP^w).
2) Cellular systems use CP, WLANs use FG (CP^c-FG^w).
3) Cellular systems use FG, WLANs use CP (FG^c-CP^w).
4) Cellular systems and WLANs both use FG (FG^c-FG^w).

For any of the above, different parameters $T_{i_s}^c$ and $T_{k_s}^w$ can lead to different performance. The questions are: *Which of the four possible combined policies should be used? How should the corresponding parameters be chosen?* To answer these questions, we consider the following two optimization problems, given the policy functions and network parameters:

Optimization Problem 1: Maximize a linear objective function of the accepting probabilities for connection requests from new and handoff users:

$$\underset{T_{i_s}^c, T_{k_s}^w}{\textbf{maximize}} \sum_{s\in S} \sum_{i\in M^c} \Bigg[\alpha_{h_{i_s}}^c (1 - B_{h_{i_s}}^c) + \alpha_{n_{i_s}}^c (1 - B_{n_{i_s}}^c) + \sum_{k\in W_i^c} \alpha_{h_{k_s}}^w (1 - B_{h_{k_s}}^w) + \alpha_{n_{k_s}}^w (1 - B_{n_{k_s}}^w)\Bigg], \tag{22}$$

where constant parameters $\alpha_{h_{i_s}}^c$ and $\alpha_{h_{k_s}}^w$ denote the *revenue* of *accepting* a connection request for service s from a handoff user in cell i and WLAN k, respectively. Similarly, $\alpha_{n_{i_s}}^c$ and $\alpha_{n_{k_s}}^w$ denote the revenue of accepting a connection request for service s from a new user in cell i and WLAN k, respectively. In general, it is reasonable to set $\alpha_{n_{i_s}}^c \ll \alpha_{h_{i_s}}^c$ for all $i \in M^c$ and $s \in S$ to make sure that higher priority is considered for accepting connection requests from handoff users rather than new users. We can also assign different revenues for different services. It is especially useful when the services are offered with different service fees.

By taking out the constant terms, problem (22) is reduced to the following *equivalent* blocking cost minimization problem:

$$\underset{T_{i_s}^c, T_{k_s}^w}{\textbf{minimize}} \sum_{s \in S} \sum_{i \in M^c} \Bigg[\alpha_{h_{i_s}}^c B_{h_{i_s}}^c + \alpha_{n_{i_s}}^c B_{n_{i_s}}^c + \sum_{k \in W_i^c} \alpha_{h_{k_s}}^w B_{h_{k_s}}^w + \alpha_{n_{k_s}}^w B_{n_{k_s}}^w \Bigg]. \quad (23)$$

In (23), parameter $\alpha_{h_{i_s}}^c$ now denotes the *cost* of *blocking* a connection request for service s from a handoff user in cell i. The other parameters can also be interpreted similarly.

Optimization Problem 2: Minimize a linear function of the required channels (i.e., BBUs) in each cell and WLAN subject to constraints on blocking probabilities and capacities:

$$\begin{array}{lll} \underset{T_{i_s}^c, T_{k_s}^w, C_i^c, C_k^w}{\textbf{minimize}} & \displaystyle\sum_{i \in N^c} \Big[C_i^c + \sum_{k \in W_i^c} C_k^w \Big] & \\ \textbf{subject to} & B_{h_{i_s}}^c \leq \Gamma_{h_{i_s}}^c, & \forall\, i \in N^c,\ \forall\, s \in S, \\ & B_{h_{k_s}}^w \leq \Gamma_{h_{k_s}}^w, & \forall\, k \in W_i^c,\ \forall\, s \in S, \\ & B_{n_{i_s}}^c \leq \Gamma_{n_{i_s}}^c, & \forall\, i \in N^c,\ \forall\, s \in S, \\ & B_{n_{k_s}}^w \leq \Gamma_{n_{k_s}}^w, & \forall\, k \in W_i^c,\ \forall\, s \in S, \\ & C_i^c \leq C_{i_{max}}^c, & \forall\, i \in N^c,\ \forall\, s \in S, \\ & C_k^w \leq C_{k_{max}}^w, & \forall\, k \in W_i^c,\ \forall\, s \in S, \end{array} \quad (24)$$

where $\Gamma_{h_{i_s}}^c$ and $\Gamma_{h_{k_s}}^w$ are the maximum blocking probabilities allowed for handoff connection requests, $\Gamma_{n_{i_s}}^c$ and $\Gamma_{n_{k_s}}^w$ are the maximum blocking probabilities allowed for new connection requests, and $C_{i_{max}}^c$ and $C_{k_{max}}^w$ are the maximum supported capacities in cell i and WLAN k, respectively. Here we assume that the number of available channels in each network is an unknown variable (rather than a given parameter) which should be determined. Problem (24) is a resource allocation problem.

IV. Numerical Results

We evaluate an integrated cellular/WLAN system consisting of a cellular network with $|M^c| = 3$ cells, and $|W_i^c| = 2$ WLANs. In each cell i and in each WLAN k, the network capacity is modeled as $C_i^c = 20$ BBUs and $C_k^w = 54$ BBUs, respectively. We assume that two different multimedia services are offered (i.e., $S = \{1, 2\}$). QoS provisioning requires that $b_1 = 1$ BBU and $b_2 = 2$ BBU. In our study, we consider different traffic patterns by assigning different values to parameters $\lambda_{i_s}^c$ and $\lambda_{k_s}^w$ for all $s \in S$. Connection duration times have means $1/\upsilon_1 = 1/\upsilon_2 = 6$ minutes. The inter-boundary time in cell i has mean $1/\eta_i^c = 2$ minutes, and the inter-boundary time in WLAN k has mean $1/\eta_k^w = 4$ minutes. The coverage factor R_{jk} is 0.5. For all $i \in M^c$ and $k \in W_i^c$, the previous values specify, $q_{i_1}^c = q_{i_2}^c = 0.25$ and $q_{k_1}^w = q_{k_2}^w = 0.40$, which define a mobility level of 75% for the cellular network, and a lower mobility level of 60% for WLANs (i.e., 75% and 60% of the users perform handoffs).

Variables $T_{i_s}^c$ and $T_{k_s}^w$ for all $i \in M^c$, $k \in W_i^c$, and $s \in S$ are integer valued, problems (22)-(24) are *combinatorial* problems. We solve them by using *exhaustive search*. For each problem, we consider all policy combinations, and obtain the global optimums for each case. The optimization search and the fixed-point algorithm are implemented in MATLAB.

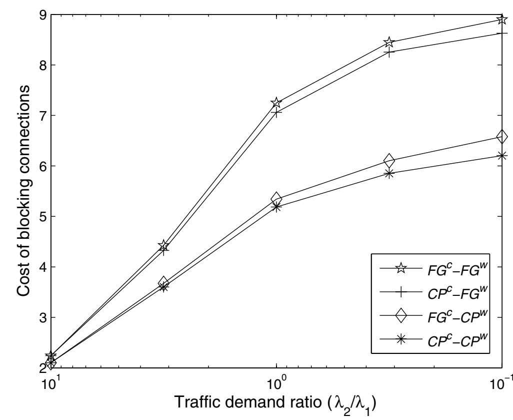

Fig. 2. Cost of blocking connections versus traffic demand ratio λ_2/λ_1.

Fig. 2 shows the optimal values obtained from each combined policy for the cost minimization version of the first optimization problem. We assume that, for all $i \in M^c$, $k \in W_i^c$, and $s \in S$, $\alpha_{n_{i_s}}^c = \alpha_{n_{k_s}}^w = 1$ and $\alpha_{h_{i_s}}^c = \alpha_{h_{k_s}}^w = 5$. That is, we assign five times higher priority to accept connection requests from handoff users compared to new users. In each figure, five different traffic patterns are considered, where for all $i \in M^c$ and $k \in W_i^c$ we have, $\lambda_{i_2}^c/\lambda_{i_1}^c = \lambda_{k_2}^w/\lambda_{k_1}^w = \lambda_2/\lambda_1$. Note that, in all cases, the aggregated traffic demand is constant in the sense that there are $\lambda_{i_1}^c + \lambda_{i_2}^c = 1$ and $\lambda_{i_1}^w + \lambda_{i_2}^w = 4$ new connection requests per minute. Finally, since $b_2 > b_1$, the aggregated traffic demand (i.e., $\lambda_{i_1}^c b_1 + \lambda_{i_2}^c b_2$) increases as ratio λ_2/λ_1 decreases.

It is observed that the best result is for CP^c-CP^w combined policy. For the higher traffic demand point, CP^c-CP^w achieves 30% lower cost of blocking connections compared to FG^c-FG^w. Recall that cost minimization is equivalent to revenue maximization. The best policy in this case, is the one that most favors handoff requests. We also observe that FG^c-FG^w and CP^c-FG^w as well as CP^c-CP^w and FG^c-CP^w policies converge to the same performance when the traffic demand decreases and hence the blocking probabilities.

Fig. 3 shows the optimal values obtained from each combined policy for the second optimization problem with constraints: $\Gamma_{h_{i_1}}^c = \Gamma_{h_{k_1}}^w = 1\%$, $\Gamma_{h_{i_2}}^c = \Gamma_{h_{k_2}}^w = 5\%$, $\Gamma_{n_{i_1}}^c = \Gamma_{n_{k_1}}^w = 5\%$, $\Gamma_{n_{i_2}}^c = \Gamma_{n_{k_2}}^w = 10\%$, $C_{i_{max}}^c = 40$, and $C_{k_{max}}^w = 60$. The number of required channels (or BBUs) increases as the traffic demand increases. Based on the proposed network parameters and constraints, CP^c-CP^w combined policy again proves to be the best solution for admission control in our proposed integrated cellular/WLAN system. As an example of the optimizing variables, when $\lambda_2/\lambda_1 = 10^{-1}$ and CP^c-CP^w being used, from the second problem we have, $C_i^{c*} = 37$, $C_k^{w*} = 44$, $T_{i_1}^{c*} = 35$, $T_{i_2}^{c*} = 33$, $T_{i_1}^{w*} = 42$ and $T_{i_2}^{w*} = 38$ for all $i \in M^c$ and $k \in W_i^c$. Finally, Fig. 4 shows the blocking probabilities for new and handoff connection requests and maximum blocking constraints for the same traffic demands using the above mentioned optimal parameters.

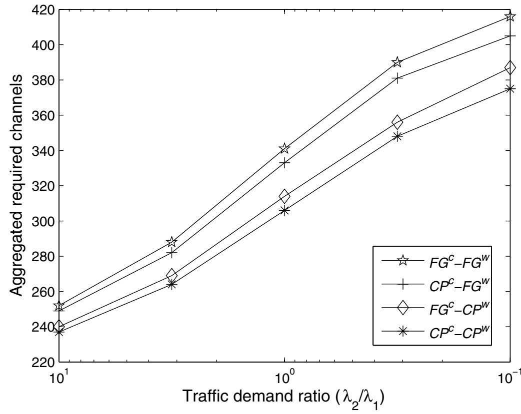

Fig. 3. Required channels versus traffic demand ratio λ_2/λ_1.

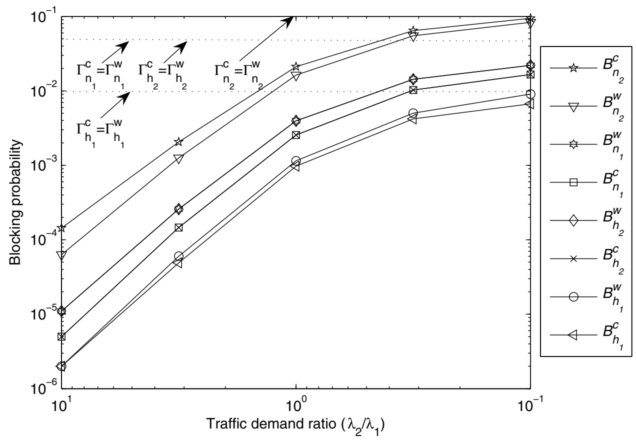

Fig. 4. New connection and handoff blocking probabilities for CP^c-CP^w.

V. Conclusions

In this paper, we developed an analytical model to facilitate the optimal evaluation of different admission control policies in a multi-service integrated cellular/WLAN system. Our model takes into account the mobility and traffic patterns, the capacity and coverage area of each network, admission control policies, revenue from offering each service, and QoS requirements. Given the model, we formulate two optimization problems to adjust admission control parameters. The first problem is to maximize the network revenue while the second problem is to minimize the required network resources subject to QoS constraints. We show that, if the parameters are chosen properly, a combination of two cutoff priority policies achieves the best solution for both problems.

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Appendix

We assume that the media access in WLAN k is controlled using DCF with carrier sense multiple access with collision avoidance (CSMA/CA). Let U_s denote the set of connected users of service s. Also let f_u denote the fraction of time that user u is active (i.e., it transmits/receives data from the access point). According to the *protocol interference model* [15], it is necessary to have,

$$\sum_{s \in S} \sum_{u \in U_s} f_u \leq 1. \qquad (25)$$

Since only one user can be active at a time when DCF is being used, an active user transmits/receives data at nominal rate C_k^w. To serve user $u \in U_s$, it is necessary that:

$$b_s = f_u C_k^w, \qquad (26)$$

where $f_u C_k^w$ denotes the effective data rate achieved by user u. From (26), we have:

$$\sum_{s \in S} \sum_{u \in U_s} f_u = \sum_{s \in S} \sum_{u \in U_s} \frac{b_s}{C_k^w} = \frac{1}{C_k^w} \sum_{s \in S} m_{k_s}^w b_s, \qquad (27)$$

where we used the fact that $|U_s| = m_{k_s}^w$. Replacing (27) in (25), inequality (6) is obtained. The proof when PCF is being used can be derived similarly.

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