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Efficient Radio Resource Management in Integrated WLAN/CDMA Mobile Networks

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Abstract. The complementary characteristics of wireless local area networks (WLANs) and wideband code division multiple access (CDMA) cellular networks make it attractive to integrate these two technologies. How to utilize the overall radio resources optimally in this heterogeneous integrated environment is a challenging issue. This paper proposes an optimal joint session admission control scheme for multimedia traffic that maximizes overall network revenue with quality of service (QoS) constraints over both WLANs and CDMA cellular networks. WLANs operate under IEEE 802.11e medium access control (MAC) protocol, which supports QoS for multimedia traffic. A cross-layer optimization approach is used in CDMA networks taking into account both physical layer linear minimum mean square error (LMMSE) receivers and network layer QoS requirements. Numerical examples illustrate that the network revenue earned in the proposed joint admission control scheme is significantly more than that when the individual networks are optimized independently.

Keywords: radio resource, WLAN, CDMA, admission control

1. Introduction

In recent years, wireless local area network (WLAN)-based systems are emerging as a popular means of wireless public access. While WLANs offer relatively high data rates to users with low mobility over smaller areas (hotspots), wideband code division multiple access (CDMA) cellular networks such as Universal Mobile Telecommunications System (UMTS) provide always on, wide-area connectivity with low data rates to users with high mobility. The complementary characteristics of WLANs and CDMA cellular networks make it attractive to integrate these two technologies [1,6,8,16,17].

In integrated WLAN/CDMA systems, a mobile user of a laptop/handheld that supports both WLAN and CDMA access capabilities can connect to both networks by roaming agreements [1,8]. Vertical handoff (also referred as handover in the literature) between WLANs and CDMA networks can be seen as the next evolutionary step from roaming in this integrated environment. The support of vertical handoff provides mobile users ongoing session continuity, in spite of movements across and between WLANs and CDMA networks [8,16].

Although some work has been done to integrate WLANs and CDMA networks, most of previous work concentrates on architectures and mechanisms to support roaming and vertical handoff, and how to utilize the overall radio resources optimally subject to quality of service (QoS) constraints for multimedia traffic is largely ignored in this coupled environment. As a consequence, WLANs and CDMA networks are studied and optimized independently in the literature. However, the interplay between WLANs and CDMA networks plays an important role in designing the integrated systems. Therefore, the schemes optimized for only one network (WLAN or CDMA network) may result in unsatisfactory performance for the overall integrated systems. In order to fully utilize the best of these two wireless access technologies, it is very important to consider the radio resources jointly. Authors in [6,17] make fine attempts in this direction by proposing architectures and schemes for joint radio resource management and QoS provisioning. Particularly, a *joint session admission control* (JSAC) function for multimedia traffic is identified as a crucial unit to utilize the overall radio resources efficiently in integrated WLAN/CDMA systems. However, no further development about an *optimal* JSAC scheme is reported in [6,17].

In this paper, we propose an optimal joint session admission control scheme for multimedia traffic in an integrated WLAN/CDMA system with vertical handoff, which maximizes the overall network revenue while satisfying several QoS constraints in both WLANs and CDMA networks. The proposed scheme can optimally control whether or not to admit as well as which network (WLAN or CDMA network) to admit a new session arrival or a vertical handoff session between WLANs and CDMA networks.

We compare our scheme with other WLAN/CDMA integration schemes. It is shown that the proposed scheme results in significant revenue gain over the schemes in which optimization is done independently in individual networks.

The rest of the paper is organized as follows. Section 2 introduces integrated WLAN/CDMA systems and the joint session admission control problem. Section 3 describes the QoS considerations in WLANs and CDMA networks. Section 4 presents our new approach to solve the joint session admission control problem. Section 5 presents some implementation issues and extensions of our scheme. Some numerical examples are given in Section 6. Finally, we conclude this study in Section 7.

2. Integrated WLAN/CDMA systems and the joint session admission control problem

In this section, we introduce integrated WLAN and CDMA cellular networks. Then, we present the joint admission control problem in this integrated environment.

2.1. Integrated WLAN/CDMA systems

There are two different ways of designing an integrated WLAN/CDMA network architecture defined as tight coupling and loose coupling inter-working [1,8].

In a tightly coupled system, a WLAN is connected to a CDMA core network in the same manner as other CDMA radio access networks. The main advantage of this solution is that the mechanism for authentication, mobility and QoS in the CDMA core network can be reused directly over the WLAN. However, this approach requires the modifications of the design of CDMA networks to accommodate the increased traffic from WLANs.

In the loose coupling approach, a WLAN is not connected directly to CDMA network elements. Instead, it is connected to the Internet. In this approach, the WLAN traffic would not go through the CDMA core network. Nevertheless, as peer IP domains, they can share the same subscriber database for functions such as security, billing and customer management.

Since mobile users are free to move in integrated WLAN/CDMA systems, the support of handoff between these two networks, which provides ongoing service continuity and seamlessness, is needed in this integration. Handoffs between WLANs and CDMA networks are commonly referred as vertical handoffs [16].

2.2. Joint session admission control

To support QoS for multimedia traffic in WLANs, an efficient admission control scheme is required in IEEE 802.11e WLANs [5,15]. On the other hand, admission control is also crucial in designing CDMA networks [2,9]. Since joint radio resource management in integrated WLAN/CDMA systems is largely ignored in most of previous work, the admission control schemes in these two networks are studied and optimized independently. However, in the coupled WLAN/CDMA environment, the schemes optimized for only one network (WLAN or CDMA network) may not be optimal for the overall integrated system. In order to utilize overall radio resources efficiently, a joint session admission control (JSAC) is very important in the integration of these two wireless access technologies [6,17].

The problem of JSAC in integrated WLAN/CDMA systems is whether or not to admit and which network (WLAN or CDMA network) to admit a new or handoff session arrival. An optimal JSAC should maximize the long-term network revenue and guarantee QoS constraints for multimedia traffic in both WLANs and CDMA networks.

Since the charging methods in WLANs are usually different from those in CDMA networks, we should consider the different revenue rates in the design of a JSAC. For the QoS constraints in WLANs, throughput and packet delay are important metrics [5,15]. In CDMA networks, QoS requirements are characterized by SIR. In addition, at the network layer of integrated WLAN/CDMA systems, QoS metrics are blocking probabilities of new or handoff sessions in both networks, which should also be guaranteed.

3. QoS in WLANs and CDMA cellular networks

In this section, we formulate the QoS metrics in WLANs and CDMA cellular networks. These QoS metrics will be used in the design of the optimal joint session admission control scheme in Section 4.

3.1. QoS in WLANs

Medium access control (MAC) protocols in IEEE 802.11 WLANs significantly affect the QoS metrics. To support QoS for multimedia traffic in WLAN, a new MAC protocol, IEEE 802.11e, is proposed [4]. The IEEE 802.11e MAC employs a channel access function called hybrid coordination function (HCF), which includes a contention-based HCF part and a contention-free part. The contention-based HCF part is also called enhanced distributed coordination function (EDCF). EDCF provides differentiated access to the wireless medium for up to 8 priorities. An access category (AC) mechanism is defined to support the priorities. There are four access categories (ACs). For access category j, $j = 1, 2, 3, 4$, there is a set of parameters, including transmission opportunity ($TXOP_j$), arbitration inter-frame space number ($AIFSN_j$), minimum contention window ($CW_{j,\min}$), maximum contention window ($CW_{j,\max}$), and maximum backoff stage (m_j). which are announced by the access point (AP).

We adopt the derivations of throughput and packet delay for IEEE 802.11e in [5] in this paper. Let ϵ denote the length of a time slot, M denote the average bit rate of the WLAN, T_{SIFS} denote the duration of a short inter-frame space (SIFS), T_{RTS}, T_{CTS}, T_{ACK}, T_{PHY} and T_{MAC} denote the time required to transmit a request-to-send (RTS), a clear-to-send (CTS), an ACK, a physical layer header and an MAC header, respectively. There are J classes of multimedia traffic with distinct QoS requirements in the system. The number of class j, $j = 1, 2, \ldots, J$, sessions in the WLAN is $n_{w,j}$. Assume that a class j, $j = 1, 2, \ldots, J$, packet has a constant probability of collision p_j, all class j packets have the same length S_j, and the propagation delay of all packets is constant π. The average backoff counter of the class j station $\mathbf{E}[BO_j]$ is $(1-2p_j)(CW_{j,\min}-1)+p_jCW_{j,\min}(1-(2p_j)^{m_j})/2(1-2p_j)$. The probability for a class j station to transmit a packet is $q_j = 2(1-2p_j)/(1-2p_j)(CW_{j,\min}+1+AIFSN_j)+p_jCW_{j,\min}[1-(2p_k)^{m_j}]$. The probability of collision can be calculated as $p_j = 1-(1-q_j)^{(n_{w,j}-1)}\prod_{1\le i\le J, i\ne j}(1-q_j)^{n_{w,i}}$. q_j and p_j can be obtained by solving the above equations using numerical techniques. The saturation bandwidth for class j traffic is [5]

$$B_j = \frac{V_j}{T_I + T_C + T_S}, \tag{1}$$

where V_j, T_I, T_C and T_S are the number of bits successfully transmitted for class j, the average time of all idle periods, the average time of all collision periods and the average time of the successful transmission period, respectively, during a transmission cycle.

The average packet delay of class j traffic is [5]

$$D_j = b_j + \frac{a_j p_j}{(1 - p_j)^2}, \tag{2}$$

where $b_j = (1/U_j)[\epsilon \mathbf{E}[BO_j] + 4T_{\text{SIFS}} + \epsilon AIFSN_j + T_{\text{RTS}} + 3\pi + T_{\text{CTS}} + T_{\text{PHY}} + T_{\text{MAC}} + L_j/M + T_{ACK} + (N_j - 1)(2T_{\text{SIFS}} + T_{\text{PHY}} + T_{\text{MAC}} + S_j/M + 2\pi + T_{\text{ACK}})]$ and $a_j = (1/U_j)(\epsilon \mathbf{E}[BO_j] + T_{\text{SIFS}} + \epsilon AIFSN_j + T_{\text{RTS}} + T_{\text{SIFS}} + \pi)$.

The throughput constraints and average packet delay constraints will be satisfied if the vector $x_w = (n_{w,1}, n_{w,2}, \ldots, n_{w,J})$ lies within the WLAN admissible set

$$X_W = \{x_w \in \mathbb{Z}_+^J : B_j \geq TB_j, D_j \leq TD_j, j = 1, 2, \ldots, J\}, \tag{3}$$

where B_j is defined in (1), D_j is defined in (2), TB_j and TD_j are the target throughput and the target average packet delay, respectively, for class j traffic.

3.2. *QoS in CDMA cellular networks*

QoS requirements in CDMA systems are characterized by signal-to-interference ratio (SIR). In order to study the SIR, we derive the asymptotic system capacity and the minimum transmit power control solution for CDMA networks with linear minimum mean square error (LMMSE) receivers.

Consider a synchronous CDMA system with spreading gain N and K sessions.[1] There are J classes of multimedia traffic in the system. An important physical layer performance measure of class j sessions is the signal-to-interference ratio, SIR_j, which should be kept above the target value ω_j. The signature sequences of all sessions are independent and randomly chosen. Due to multi-path fading, each user appears as L resolvable paths or components at the receiver. The path l of user k is characterized by its estimated average channel gain $\bar{h}_{kl}$ and its estimation error variance ξ_k^2. Linear minimum mean square error (LMMSE) detectors are used at the receiver to recover the transmitted information. In a large system (both N and K are large) with background noise σ^2, the SIR for the LMMSE receiver of a user (say, the first one) can be expressed approximately as [3] $\text{SIR}_1 = (P_1 \sum_{l=1}^{L} |\bar{h}_{1l}|^2 \eta)/(1 + P_1 \xi_1^2 \eta)$, where P_1 is the attenuated transmitted power from user 1, η is the unique fixed point in $(0, \infty)$ that satisfies $\eta = [\sigma^2 + (1/N) \sum_{k=2}^{K}((L-1)I(\xi_k^2, \eta) + I(\sum_{l=1}^{L} |\bar{h}_{kl}|^2 + \xi_k^2, \eta))]^{-1}$ and $I(\nu, \eta) = \nu/(1+\nu\eta)$. In [2], it is shown that a minimum received power solution exists such that all sessions

[1] The proposed approaches are also applicable to an asynchronous CDMA system. In [11], it is shown that an asynchronous CDMA system with K users can be viewed as a synchronous CDMA system with MK users, where M is the frame length. For simplicity of the presentation, we only consider synchronous systems in this paper.

in the system meet their target SIRs if and only if

$$\omega_j < \frac{|\bar{h}_j|^2}{\xi_j^2} \quad \text{and} \quad \frac{1}{N}\sum_{j=1}^{J}\sum_{i=1}^{n_{c,j}} R_j^i \Upsilon_j < 1, \tag{4}$$

where $|\bar{h}_j|^2 = \sum_{l=1}^{L} |\bar{h}_{jl}|^2$, $j = 1, 2, \ldots, J$, $n_{c,j}$ is the number of class j sessions in the CDMA cell, R_j^i is the number of signature sequences assigned to the ith session of class j to make it transmit at R_j^i times the basic rate (obtained using the highest spreading gain N) and

$$\Upsilon_j = (L-1)\omega_j \frac{\xi_j^2}{|\bar{h}_j|^2} + \frac{\omega_j\left(1 + \frac{\xi_j^2}{|\bar{h}_j|^2}\right)}{1+\omega_j}. \tag{5}$$

The minimum received power solution for a class 1 session is

$$P_1 = \frac{\omega_1 \sigma^2}{|\bar{h}_1|^2\left(1 - \omega_1 \frac{\xi_1^2}{|\bar{h}_1|^2}\right)\left(1 - \frac{1}{N}\sum_{j=1}^{J}\sum_{i=1}^{n_{c,j}} R_j^i \Upsilon_j\right)}. \tag{6}$$

The SIR constraints will be satisfied if the vector $x_c = (n_{c,1}, n_{c,2}, \ldots, n_{c,J})$ lies within the CDMA admissible set

$$X_C = \left\{ x_c \in \mathbb{Z}_+^J : \frac{1}{N}\sum_{j=1}^{J}\sum_{i=1}^{n_{c,j}} R_j^i \Upsilon_j < 1,\ j = 1, 2, \ldots, J \right\}. \tag{7}$$

4. Optimal joint session admission control

In this section, the optimal session admission control (JSAC) problem is formulated as a semi-Markov decision process (SMDP) [7]. When a new or vertical handoff session arrives, a decision must be made whether or not to admit and which network (WLAN or CDMA network) to admit the arrival. These time instants are called *decision epochs* and decisions are called *actions* in the SMDP framework. The action chosen is based on the current *state* of the integrated system. The state information includes the number of sessions of each class of traffic in both the WLAN and the CDMA network. The QoS constraints in both networks described in Section 3 are incorporated by truncating the state space to those points that satisfy the constraints. The optimality criterion for the SMDP is the long-run average reward per unit time. A linear programming (LP) algorithm is used to provide the optimal joint admission control policy. Network layer blocking probability QoS constraints are accommodated by adding additional linear constraints to the LP. Since sample path constraints are included in the LP, the optimal policy will in general be a randomized stationary policy [10].

For simplicity of the presentation, we consider an integrated WLAN/CDMA system with a single WLAN cell and a single CDMA cell, where the WLAN coverage is within the CDMA cell. The generalization of our scheme to multiple WLAN and CDMA cells is given in Section 5. We divide the CDMA cell into two areas, CDMA area and WLAN area. Mobile users in the WLAN area can access both the WLAN and the CDMA network, whereas mobile users in the CDMA area can only access the CDMA network. We assume that there are J classes of traffic. Class j, $j = 1, 2, \ldots, J$, new sessions arrive according to a Poisson distribution with the rate of $\lambda_{c,n,j}$ ($\lambda_{w,n,j}$) in the CDMA (WLAN) area. The total new session arrival rate for class j traffic is $\lambda_{n,j} = \lambda_{c,n,j} + \lambda_{w,n,j}$. Class j handoff sessions depart from the CDMA network (WLAN) to the WLAN (CDMA network) according to a Poisson distribution with rate of $\mu_{c,h,j}$ ($\mu_{w,h,j}$). Session duration time for class j traffic is exponentially distributed with the mean $1/\mu_{c,t}$ ($1/\mu_{w,t}$) in the CDMA (WLAN) area.

In order to obtain the optimal solution, it is necessary to identify the state space, decision epochs, actions, state dynamics, reward and constraints in the integrated WLAN/CDMA system.

4.1. State space

Define row vector $x_w(t) = [n_{w,1}(t), n_{w,2}(t), \ldots, n_{w,J}(t)] \in \mathbb{Z}_+^J$, where $n_{w,j}(t)$ denotes the number of class j sessions in the WLAN. Define row vector $x_c(t) = [n_{c,1}(t), n_{c,2}(t), \ldots, n_{c,J}(t)] \in \mathbb{Z}_+^J$, where $n_{c,j}(t)$ denotes the number of class j sessions in the CDMA cell. The state space X of the system comprises of any state vector such that the throughput and average packet delay constraints in the WLAN cell and the SIR constraints in the CDMA cell can be met. Therefore, the state space of the SMDP can be defined as

$$X = \left\{ x = [x_w, x_c] \in \mathbb{Z}_+^{2J} : B_j \geq TB_j,\ D_j \leq TD_j,\ \frac{1}{N} \sum_{j=1}^{J} \sum_{i=1}^{n_{c,j}} R_j^i \Upsilon_j < 1,\ j = 1, 2, \ldots, J \right\}, \tag{8}$$

where B_j, D_j and Υ_j are defined in (1), (2) and (5), respectively.

4.2. Decision Epochs and actions

We choose the decision epochs to be the set of all session arrival and departure instances. Let $t_0 = 0$. The decision epochs are taken to be the instances t_k, $k = 0, 1, 2, \ldots$. At each decision epoch t_k, the network makes a decision for each possible session arrival that may occur in the time interval $(t_k, t_{k+1}]$. Action $a(t_k)$ at decision epoch t_k is defined as $a(t_k) = [a_{c,n}(t_k), a_{c,h}(t_k), a_{w,n}(t_k), a_{w,h}(t_k)]$, where $a_{c,n}(t_k)$, $a_{c,h}(t_k)$, $a_{w,n}(t_k)$, $a_{w,h}(t_k)$ are defined and interpreted as follows. (1) Define row vector $a_{c,n}(t_k) = [a_{c,n,1}(t_k), a_{c,n,2}(t_k), \ldots, a_{c,n,J}(t_k)] \in \{0, 1\}^J$, where $a_{c,n,j}(t_k)$ denotes the action for class j new session arrivals in the CDMA area. If $a_{c,n,j}(t_k) = 1$, a new class j session that arrives in the CDMA area is admitted to the CDMA network. If $a_{c,n,j} = 0$, it is rejected. (2) $a_{c,h}(t_k)$ is defined similarly for handoff session arrivals in the CDMA area. (3) Define row vector $a_{w,n}(t_k) = [a_{w,n,1}(t_k), a_{w,n,2}(t_k), \ldots, a_{w,n,J}(t_k)] \in \{-1, 0, 1\}^J$, where $a_{w,n,j}(t_k)$ denotes the action for class j new session arrivals in the WLAN area. If $a_{w,n,j}(t_k) = 1$, a new class j session that arrives in the WLAN area is admitted to the WLAN. If $a_{w,n,j} = -1$, it is admitted to the CDMA network. If $a_{w,n,j} = 0$, it is rejected. (4) Define row vector $a_{w,h}(t_k) = [a_{w,h,1}(t_k), a_{w,h,2}(t_k), \ldots, a_{w,h,J}(t_k)] \in \{0, 1\}^J$, where $a_{w,h,j}(t_k)$ denotes the action for class j handoff arrivals to the WLAN cell. If $a_{w,h,j}(t_k) = 1$, a handoff class j session that arrives in the WLAN area is admitted to the WLAN network, if $a_{c,h,j} = 0$, it is kept in the CDMA network.

The action space can be defined as $A = \{a = [a_{c,n}, a_{c,h}, a_{w,n}, a_{w,h}] : a_{c,n} \in \{0, 1\}^J, a_{c,h} \in \{0, 1\}^J, a_{w,n} \in \{-1, 0, 1\}^J, a_{n,h} \in \{0, 1\}^J, j = 1, 2, \ldots, J\}$. For a given state $x \in X$, a selected action should not result in a transition to a state that is not in X. In addition, action $(0, 0, \ldots, 0)$ should not be a possible action in state $(0, 0, \ldots, 0)$. Otherwise, new sessions are never admitted into the network and the system cannot evolve. The action space of a given state $x \in X$ is defined as

$$\begin{aligned} A_x = \{a \in A : a_{w,n,j} \neq 1 \text{ and } a_{w,h,j} = 0 \text{ if } [(x_w + e_j^u), x_c] \notin X, a_{c,n,j} = 0 \text{ and } \\ a_{c,h,j} = 0 \text{ if } [x_w, (x_c + e_j^u)] \notin X,\ j = 1, 2, \ldots, J, \text{ and } \\ a \neq (0, 0, \ldots, 0) \text{ if } x = (0, 0, \ldots, 0)\}, \end{aligned} \tag{9}$$

where $e_j^u \in \{0, 1\}^J$ denotes a row vector containing only zeros except for the jth component, which is 1. $x_w + e_j^u$ corresponds to an increase of the number of class j sessions by 1 in the WLAN. $x_c + e_j^u$ corresponds to an increase of the number of class j sessions by 1 in the CDMA cell.

4.3. State dynamics

The state dynamics of the system can be characterized by the state transition probabilities of the embedded chain and the expected sojourn time $\tau_x(a)$ for each state-action pair. The cumulative event rate is the sum of the rates of all constituent processes and the expected sojourn time is the inverse of the event rate

$$\begin{aligned} \tau_x(a) = \Bigg[\sum_{j=1}^{J} (\lambda_{c,n,j} a_{c,n,j} + \mu_{w,h,j} n_{w,j} + \lambda_{w,n,j} |a_{w,n,j}| + \mu_{c,h,j} n_{c,j} a_{w,h,j}) \\ + \sum_{j=1}^{J} (\mu_{c,t,j} n_{c,j} + \mu_{w,t,j} n_{w,j}) \Bigg]^{-1}. \end{aligned} \tag{10}$$

The state transition probabilities of the embedded Markov chain are

$$p_{xy}(a) = \begin{cases} [\lambda_{c,n,j} a_{c,n,j} + \lambda_{w,n,j} \delta(-a_{w,n,j})] \tau_x(a), & \text{if } y = \left[x_c + e_j^u, x_w\right] \\ \lambda_{w,n,j} \delta(a_{w,n,j}) \tau_x(a), & \text{if } y = \left[x_c, x_w + e_j^u\right] \\ \mu_{w,h,j} n_{w,j} a_{c,h,j} \tau_x(a), & \text{if } y = \left[x_c + e_j^u, x_w - e_j^u\right] \\ \mu_{c,h,j} n_{c,j} a_{w,h,j} \tau_x(a), & \text{if } y = \left[x_c - e_j^u, x_w + e_j^u\right], \\ \mu_{c,t,j} n_{c,j} \tau_x(a), & \text{if } y = \left[x_c - e_j^u, x_w\right] \\ [\mu_{w,t,j} + \mu_{w,h,j}(1 - a_{c,h})] n_{w,j} \tau_x(a), & \text{if } y = \left[x_c, x_w - e_j^u\right] \\ 0, & \text{otherwise} \end{cases} \tag{11}$$

where $\delta(x) = 0,\ \text{if } x \leq 0$ and $\delta(x) = 1,\ \text{if } x > 0$.

4.4. *Reward function*

The average reward criterion is considered as the performance criterion in this paper. Based on the action a taken in a state x, a reward $r(x, a)$ occurs to the operator. Authors in [9] show that the blocking probability can be expressed as an average cost criterion in the CAC setting. Similarly, we use the admitting probability (1 − blocking probability) as the average reward criterion in this paper, and the proof in [9] applies directly. We define the reward for state-action pair (x, a) as

$$\begin{aligned} r(x, a) = \sum_{j=1}^{J} [& w_{c,n,j} a_{c,n,j} + w_{c,h,j} a_{c,h,j} + w_{w,n,j} \delta(a_{w,n,j}) + w_{c,n,j} \delta(-a_{w,n,j}) \\ & + w_{w,h,j} a_{w,h,j} + w_{c,n,j}(1 - a_{w,h,j})], \end{aligned} \tag{12}$$

where $w_{c,n,j}$, $w_{c,h,j}$, $w_{w,n,j}$ and $w_{w,h,j}$ are the weights associated with $a_{c,n,j}$, $a_{c,h,j}$, $a_{w,n,j}$ and $a_{w,h,j}$, respectively.

4.5. *Constraints*

In the formulated problem, throughput constraints, packet delay constraints in the WLAN and SIR constraints in the CDMA can be guaranteed by restricting the state space in (8). In addition, it is desirable for a network operator to put constraints on blocking probabilities of certain classes of traffic. Therefore, we need to formulate session blocking probability constraints in our model.

The constraints related to the new session blocking probabilities in the CDMA network can be expressed as $P^b_{c,n,j} \leq \gamma_{c,n,j}$. The new session blocking probability constraints in the CDMA networks can be easily addressed in the linear programming formulation by defining a cost function related to these constraints, $c^b_{c,n,j}(x, a) = 1 - a_{c,n,j}$. Similarly, the cost function related to the handoff session blocking probability constraints $P^j_{c,h,j} \leq \gamma_{c,h,j}$ in the CDMA network are $c^b_{c,h,j}(x, a) = 1 - a_{c,h,j}$. The cost function related to the new session blocking probability constraints $P^j_{w,n,j} \leq \gamma_{w,n,j}$ in the WLAN are $c^b_{w,n,j}(x,a) = 1 - |a_{w,n,j}|$. The cost function related to the handoff session blocking probability constraints $P^j_{w,h,j} \leq \gamma_{w,h,j}$ in the WLAN are $c^b_{w,h,j}(x,a) = 1 - a_{w,h,j}$, $j = 1, 2, \ldots, J$.

4.6. Linear programming solution to the SMDP

Due to the constraints in the above SMDP formulation, it is natural to use the linear programming methodology to compute the optimal policy. The optimal policy u^* of the SMDP is obtained by solving the following linear program (LP) [10].

$$\max_{z_{xa}\geq 0, x\in X, a\in A_x} \sum_{x\in X}\sum_{a\in A_x}\sum_{j=1}^{J} r(x,a)\tau_x(a)z_{xa}$$

subject to

$$\begin{aligned}
&\sum_{a\in A_y} z_{ya} - \sum_{x\in X}\sum_{a\in A_x} p_{xy}(a)z_{xa} = 0, \quad y \in X,\\
&\sum_{x\in X}\sum_{a\in A_x} z_{xa}\tau_x(a) = 1,\\
&\sum_{x\in X}\sum_{a\in A_x}(1 - a_{c,n,j})z_{xa}\tau_x(a) \leq \gamma_{c,n,j}, \quad j = 1, 2, \ldots, J,\\
&\sum_{x\in X}\sum_{a\in A_x}(1 - a_{c,h,j})z_{xa}\tau_x(a) \leq \gamma_{c,h,j}, \quad j = 1, 2, \ldots, J,\\
&\sum_{x\in X}\sum_{a\in A_x}(1 - |a_{w,n,j}|)z_{xa}\tau_x(a) \leq \gamma_{w,n,j}, \quad j = 1, 2, \ldots, J,\\
&\sum_{x\in X}\sum_{a\in A_x}(1 - a_{w,h,j})z_{xa}\tau_x(a) \leq \gamma_{w,h,j}, \quad j = 1, 2, \ldots, J. \qquad (13)
\end{aligned}$$

The decision variables are $z_{xa}, x \in X, a \in A_x$. Since sample path constraints are included in (13), the optimal policy obtained will be a randomized policy: The optimal action $a^* \in A_x$ for state x is chosen probabilistically according to the probabilities $z_{xa}/\sum_{a\in A_x} z_{xa}$.

4.7. Computational complexity

To obtain the optimal JSAC policy, we need to (1) construct the state space X in (8) and (2) solve the LP in (13). Both procedures are done offline. Constructing X involves a finite number of QoS constraints feasibility evaluations in both networks. Since if all sessions satisfy their QoS constraints, then the departure of any session results in the remaining users still satisfying their QoS requirements, the state space X is convex. Therefore, not each point in X needs to be checked, which greatly simplifies the procedure (1). The complexity of procedure (2) is related to the number of decision variables in the LP, which can be solved by *interior point methods*. The complexity of procedures (1) and (2) can be decreased by reducing the cardinality of the state space X, which can be achieved by reducing the number of traffic classes under considerations in integrated WLAN/CDMA systems.

4.8. Multiple WLAN and CDMA cells

We can generalize the JSAC problem to a system with multiple WLAN and CDMA cells. A straightforward approach is to include the number of sessions of each class in each cell in the state vector X (8). The state dynamics in Section 4.3 need to be revised to incorporate all the events that make the system state change. This approach will increase the state space and the computational complexity dynamically. As a consequence, LP may not be a feasible method to solve the SMDP. Fortunately, recent advances in *reinforcement learning* [12] can be used to break the curse of dimensionality. Another approach is to assume that the traffic in the integrated WLAN/CDMA system is uniformly distributed. Under this assumption, the whole system can be reduced to a single WLAN cell and a single CDMA cell. The state space in (8) remains the same. The only thing we need to change is to consider the handoff traffic to and from other cells in the state dynamics in Section 4.3.

5. Numerical results

In this section, we illustrate the performance of the proposed optimal JSAC scheme by numerical examples. We show that the proposed scheme can achieve significant performance improvement over two other WLAN/CDMA integration schemes.

One class of video traffic is considered in an integrated WLAN/CDMA system with a single WLAN cell and a single CDMA cell. Each video flow is 1.17 Mbps in the WLAN, which is generated by a constant inter-arrival time 10 ms with a constant payload size of 1464 bytes. It corresponds to a traffic-shaped constant bit rate (CBR) video flow. The numerical values for the WLAN system parameters are given in Table 1. Because of the scarce bandwidth available in cellular networks and the small screen of handsets, we assume that the bandwidth consumption of a video session is smaller in the CDMA network compared to that in the WLAN. This bandwidth adaptation can be achieved by adjust of compression parameters and coding techniques such as layered coding [13]. Specifically, the transmission rate for the video traffic in the CDMA network is 240 Kbps and correspond to an equivalent spreading gain $N = 16$, which can be interpreted as multiple code transmission using a higher spreading gain (say, $N = 256$) to ensure the accuracy of the asymptotic approximation of CDMA system with LMMSE receivers. The numerical values for CDMA network are given in Table 2. The new session arrival rates in the CDMA and the WLAN areas are $\lambda_{c,n}$ and $\lambda_{w,n}$, respectively. The total new

Table 1
WLAN parameters used in numerical examples.

Parameter	Notation	Value
average channel bit rate	M	11 Mbps
slot time	ϵ	10 μs
propagation delay	π	1 μs
time required to transmit a PHY header	T_{PHY}	48 μs
time required to transmit an MAC header	T_{MAC}	25 μs
time required to transmit a request-to-send (RTS)	T_{RTS}	15 μs
time required to transmit a clear-to-send (CTS)	T_{CTS}	10 μs
time required to transmit an ACK	T_{ACK}	10 μs
arbitration inter-frame space number (AIFSN) for video traffic	$AIFSN$	1
minimum contention window for video traffic	$CW_{\min}$	16
maximum contention window for video traffic	$CW_{\max}$	32
video packet size	V	1464 bytes

Table 2
CDMA network parameters used in numerical examples.

Parameter	Notation	Value
target SIR for video traffic	ω	10 dB
estimated average channel gain for video traffic	$\lvert\bar{h}\rvert^2$	1
channel estimation error variance for video traffic	ξ^2	0.034
number of resolvable paths	L	5
data transmission rate for video traffic	R	240 Kbps

session arrival rate is $\lambda_n = \lambda_{c,n} + \lambda_{w,n}$. $\mu_{c,t}$ and $\mu_{c,h}$ are the session termination rate and the session handoff rate, respectively, in the CDMA network. $\mu_{w,t}$ and $\mu_{w,h}$ are the session termination rate and the session handoff rate, respectively, in the WLAN.

We compare the average reward earned in the proposed scheme to those in two other WLAN/CDMA integration schemes. In the first scheme, admission control is done independently in individual networks and there is no vertical handoff between the WLAN and the CDMA network. In the second scheme, handoff between these two networks can be supported. When a mobile user with a WLAN session moves from the WLAN area, it will handoff to the CDMA network if there is free bandwidth available in the CDMA network. On the other hand, when a mobile user with a CDMA session moves into the WLAN area, it will handoff to the WLAN if there is free bandwidth there. Otherwise, the mobile user will remain in the CDMA network. Note that there is no joint session admission control and joint radio resource management in both schemes.

The percentage of reward gain is shown in figure 1. In this example, 40% of the total new session arrivals in the system occur in the WLAN area. $\mu_{c,t} = \mu_{w,t} = 0.005$, $\mu_{c,h} = 0.004$ and $\mu_{w,h} = 0.0005$. $w_{c,n} = w_{c,h} = 2$. $w_{w,n} = w_{w,h} = 1$. From figure 1,

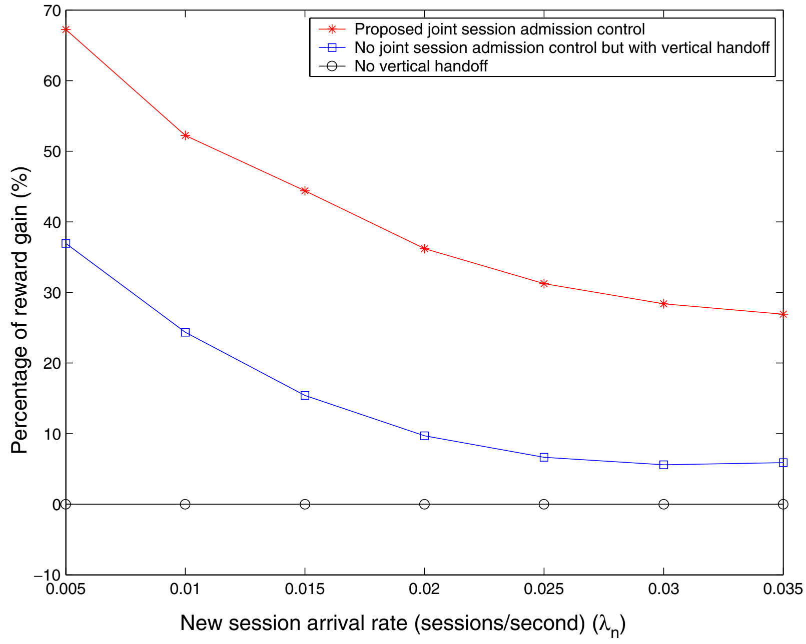

Figure 1. Percentage of reward gain.

we can see that the reward earned in the proposed scheme is always more than those in two other schemes, and the reward is the least in the scheme in which vertical handoff is not supported. It is observed that the higher the new session arrival rate, the less the percentage of reward gain. This is because the system becomes saturated when the arrival rate is high, and the proposed scheme has no much room to select sessions to admit based on the reward rate. Nevertheless, the reward earned in the proposed scheme is about 27% higher than that in the scheme without vertical handoff support even when the system is in high load.

The reward rate ratio between the CDMA network and the WLAN will be different with different network operators. If the ratio is less than 1, operators earn less reward when a session is admitted to a CDMA network instead of a WLAN. Otherwise, operators earn equal reward (ratio is 1) or more reward (ratio is greater than 1). Figure 2 show the reward gain with $\lambda_n = 0.03$. It is very interesting to observe that the reward in the scheme with vertical handoff but no joint admission control will less than that in the scheme without vertical handoff support when the ratio is larger than 2.2 in figure 2. However, the proposed scheme can always have reward gain with a large range of the ratio values.

The handoff rates, $\mu_{c,h}$ and $\mu_{w,h}$, represent how fast mobile users move around in the CDMA network and the WLAN, respectively. Figure 3 shows the effects of user mobility on the reward gain. Since mobile users in WLANs usually have slow mobility

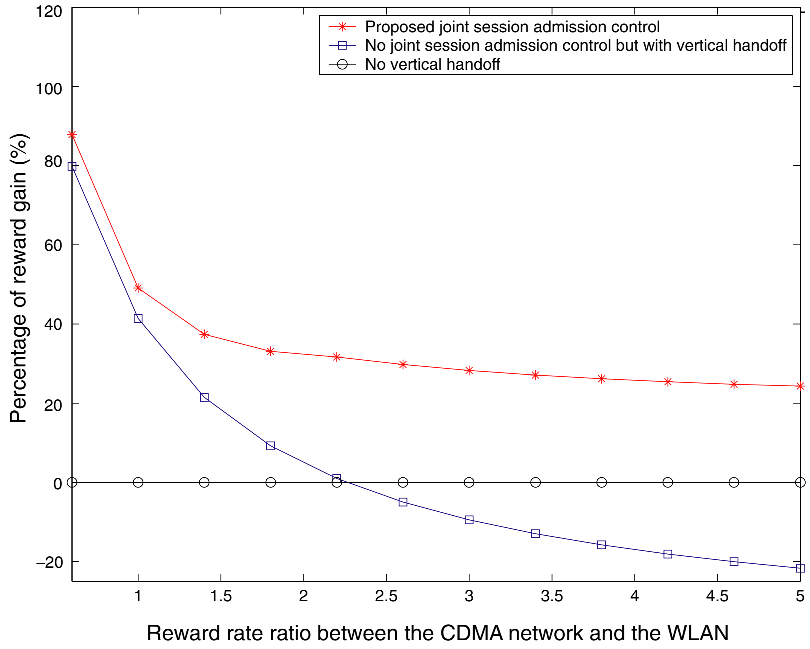

Figure 2. Percentage of reward gain vs. reward rate ratio between the CDMA network and the WLAN ($\lambda_n = 0.03$).

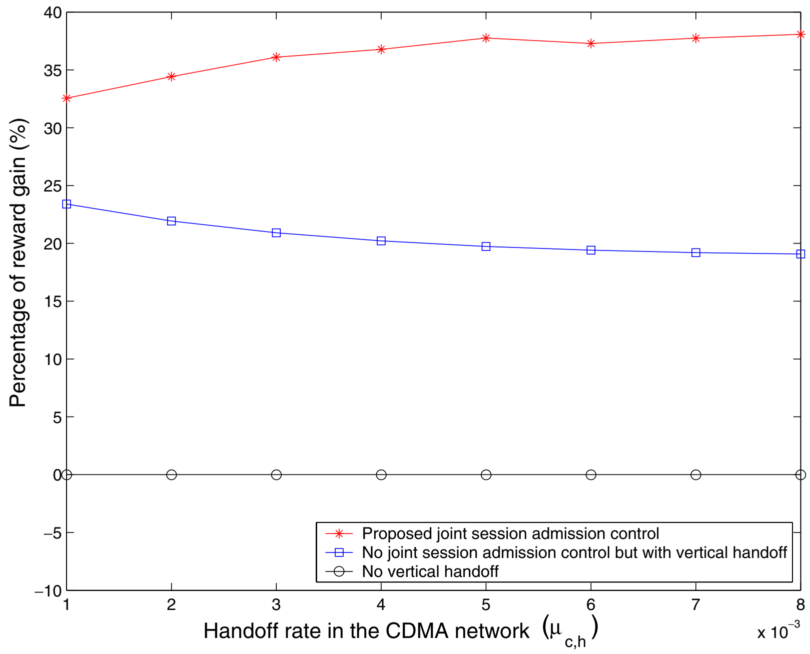

Figure 3. Percentage of reward gain vs. handoff rate in the CDMA network.

compared to those in CDMA networks, we set $\mu_{w,h} = \mu_{c,h}/5$. We can see that our scheme can have significant reward gain over the other two schemes with different user mobility rates.

6. Conclusions and future work

In this paper, we have presented an optimal joint session admission control scheme in integrated WLAN/CDMA networks to utilize the overall radio resources optimally. The proposed scheme can maximize network revenue with QoS constraints in both WLANs and CDMA cellular networks. Optimal linear-programming-based algorithms were presented. We illustrated the performance of the proposed scheme by numerical results. We found that the WLAN/CDMA integration scheme with vertical handoff but no joint admission control can have less revenue than the integration scheme without vertical handoff support. It was shown that the proposed optimal joint session admission control scheme can have a very significant gain over the schemes in which admission controls are done independently in individual networks. Future study is in progress to reduce or eliminate the signaling overhead of exchanging status information by some local estimation functions.

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