Providing Differentiated Services Over Shared Wireless Downlink Through Buffer Management

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***Abstract*—In this paper, we present an opportunistic packet scheduling algorithm based on buffer management (OSBM) over the downlink of a packet cellular network. OSBM is a channel-dependent scheduling algorithm with a provable delay bound. It is able to provide differentiated services to both real-time and nonreal-time applications. Particularly, these features of OSBM are achieved through a novel buffer management scheme. Since this buffer management scheme does not involve any complex online computation, OSBM is very efficient and easy to implement in an operational environment. We also present a new analytical approach for performance analysis of opportunistic scheduling in wireless networks based on the proposed concept of effective downlink capacity (EDC). This approach attempts to adapt the service curve tool for deterministic quality-of-service analysis to the wireless environment, and the concept of the EDC serves to bridge the deterministic method and the stochastic nature of the wireless link. Using this approach, the explicit expression of the delay bound of the OSBM algorithm is obtained. Simulation results are presented to demonstrate the effectiveness of the proposed opportunistic scheduling algorithm.**

***Index Terms*—Opportunistic scheduling, packet scheduling, quality of service (QoS), wireless downlink.**

I. Introduction

A PACKET cellular network is an attractive solution to provide a high-data-rate (HDR) service to nomadic users based on the existing cell phone infrastructure [1], [2]. With the packet cellular network as the access network that connects the mobile users and the high-speed wireline core network, end-to-end communication-intensive applications, such as video/voice conferencing and file transfer, etc., can be supported if proper packet scheduling mechanisms are in place to provide differentiated services. However, quality-of-service (QoS) provisioning over a wireless link, which is essential for real-time applications, is a challenging problem due to the following characteristics of the wireless channel: 1) Since the bandwidth of the wireless link in the cellular packet network is scarce (e.g., 2-Mb/s downlink speed in the case of the HDR service over code-division multiple-access (CDMA) link [1], [3], [4]), over provisioning is not appropriate, and an ideal scheduling algorithm must be able to efficiently use the wireless bandwidth; 2) the wireless channel is subject to transmission impairment, which requires explicit error detection and correction mechanisms; and 3) the quality of the shared wireless channel is dependent on the location of a mobile host and randomly changes over time on both slow and fast timescales [2], [3], which requires the QoS mechanism to be channel quality dependent. All these factors make the packet scheduling over wireless links more complicated than in wireline networks.

Packet scheduling in wireline packet networks has received extensive attention in the past decade [5]–[8], but direct application of the conventional packet scheduling algorithms to a wireless environment often results in poor utilization of the limited wireless bandwidth resources [9]. In the recent years, much work has been done to develop wireless scheduling algorithms, which are able to achieve high link throughput and good user fairness [9]–[13]. One of the major limitations of the existing wireless packet scheduling (WPS) algorithms is the high level of complexity in implementation. Many wireless scheduling algorithms in the literature need to emulate a wireline scheduling algorithm to find the discrepancy between the services a flow receives over the wireless link and the wireline link, based on which service compensation can be applied to achieve the idealized fairness [11], [12], [14]. Other wireless scheduling algorithms need to execute a well-known wireline scheduling algorithm with slight modification to integrate the channel condition information [9], [13]. Both approaches require extensive online computation, which makes the algorithms difficult to implement in an operational environment. The opportunistic scheduling algorithm based on buffer management (OSBM) proposed in this paper is intended to solve this problem.

OSBM employs a novel buffer management scheme to accomplish packet dispatch, transmission defer, and compensation. Based on this scheme, differentiated services are provided to real-time and nonreal-time traffic flows, which is an issue not fully addressed by the existing WPS algorithms in the literature. The packet delay of both real-time and nonreal-time flows is guaranteed, and the long-term link throughput is maintained at the expected rate. Above all, since OSBM does not involve any complex online computation, it is very efficient and easy to implement in an operational environment.

On the other hand, a service curve is a very useful tool for performance analysis in packet networks that provide

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deterministic QoS guarantees [5], [15]. However, its application in wireless networks has not received full attention because a deterministic QoS over a wireless link is impossible due to the randomly changing channel condition. Although the service curve model with loss [17] has the potential to capture the feature of unavoidable packet loss in wireless networks, it is difficult to apply this model to performance analysis in the context of this paper. Therefore, we propose a more straightforward yet effective approach to apply the service curve model in performance analysis of scheduling discipline over the wireless link based on the concept of effective downlink capacity (EDC). Based on this analytical method, an explicit expression of the delay bound of the proposed OSBM algorithm is obtained.

The rest of this paper is organized as follows: Section II presents the channel and traffic models used in this paper. Section III describes the OSBM algorithm, and the analysis of the OSBM algorithm is given in Section IV. Section V presents simulation results to illustrate the performance of the OSBM algorithm. Section VI concludes the paper.

II. Channel and Traffic Models

A. Channel Model

In this paper, we consider a packet cellular network with a high-speed wired backbone and small shared channel wireless cells. The base station in each cell performs the scheduling of packet transmissions to the mobile hosts that are randomly located in the cell. Specifically, only downlink transmission (from base station to mobile host) in a single cell is considered in the scheduling scheme. One example of the wireless system we consider in this paper is the CDMA/HDR service [1], [2], where the transmission time of the shared channel is divided into fixed-duration time slots, and only one host is allowed to use the channel in each slot.

The quality of the shared wireless channel is time varying and user location dependent [1], [2]. The channel condition experienced by a mobile host m at time slot n is translated into the feasible data rate $R_m(n)$ $(m \in \{1, 2, \ldots, M\})$, where M is the number of mobile hosts in the cell. The value of $R_m(n)$ represents the maximum data rate that can be transmitted from base station to host m in slot n if the whole channel is dedicated to host m in slot n [3]. The base station is able to keep track of the instantaneous feasible rate of all mobile hosts in the cell and make use of this information in packet scheduling.

Define $\boldsymbol{\mu} = \{\mu_1, \ldots, \mu_K\}$ $(\mu_1 < \mu_2 < \cdots < \mu_K)$ as the set of discrete data rates that are available in the underlying packet cellular network, where K is the total number of available rates. The feasible rate $R_m(n)$ for host m at the beginning of the nth time slot is chosen to be the largest available rate in the set $\boldsymbol{\mu}$ such that the signal-to-noise ratio requirement is satisfied.

Define μ_{th} as the channel threshold to distinguish a good-quality channel and a bad-quality channel. A channel is considered "good" if the instantaneous feasible rate is greater than or equal to μ_{th}; otherwise, the channel is deemed "bad." In the proposed OSBM algorithm, only hosts with good channels are allowed to transmit a packet. For notational convenience, the term "channel condition of a flow" is also used to refer to the channel condition observed by the destination host of a downlink traffic flow.

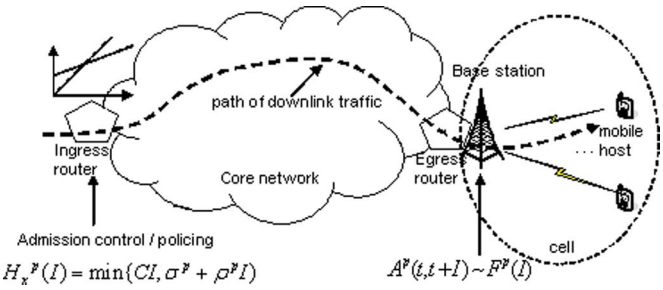


Fig. 1. Network model.

B. Traffic Model

In the context of our discussion, several downlink flows can be established between the source stations and a mobile host i $(i \in \{1, \ldots, M\})$. Based on the QoS requirements of the applications, each flow is assigned a priority p $(p \in \{1, 2, \ldots, P\})$, where P is the total number of priorities supported in the network. Specifically, priority 1 to priority P' $(P' < P)$ are assigned to real-time flows, and priority $P' + 1$ to P are assigned to nonreal-time flows. For ease of discussion, we denote by group G_i^p all the flows with priority p to host i and by group G^p all the priority p flows in the cell, regardless of the destination host of the flows.

We consider an end-to-end path traversing a high-speed core network and a wireless cell, as shown in Fig. 1. At the ingress node of the core network, a flow of priority p is leaky bucket (σ^p, ρ^p) constrained, as shown in Fig. 1. The output traffic from the leaky bucket is called "source traffic" in this paper because its burstiness and average rate can be represented by σ^p and ρ^p of the leaky bucket shaper, respectively.

To describe the arrival pattern of the downlink traffic, we define $A_x(t_1, t_2)$ as the amount of traffic from flow x that arrives during the time interval $[t_1, t_2)$ and $f_x(I)$ as the traffic constraint function of $A_x(t, t + I)$ [5], [18] such that

$$A_x(t, t + I) \leq f_x(I), \qquad \text{for } t > 0,\ I > 0. \tag{1}$$

Let $H_x^p(I)$ be the "source traffic" constraint function of a priority p flow at the ingress node, which can be written as

$$H_x^p(I) = \min\{CI, \sigma^p + \rho^p I\} \tag{2}$$

where C is the output capacity of the leaky bucket.

At the base station, $F_x(I)$ is used as the traffic constraint function for flow x. We further use $F_i^p(I)$ and $F^p(I)$ to denote the traffic constraint function at the base station for groups G_i^p and G^p, respectively.

Considering a core network with a maximum packet delay of D^p for a priority p flow, the traffic constraint function of flow x with priority p at the base station can be expressed using the source constraint function, as follows [18]:

$$F_x(I) \leq H_x^p(I + D^p). \tag{3}$$

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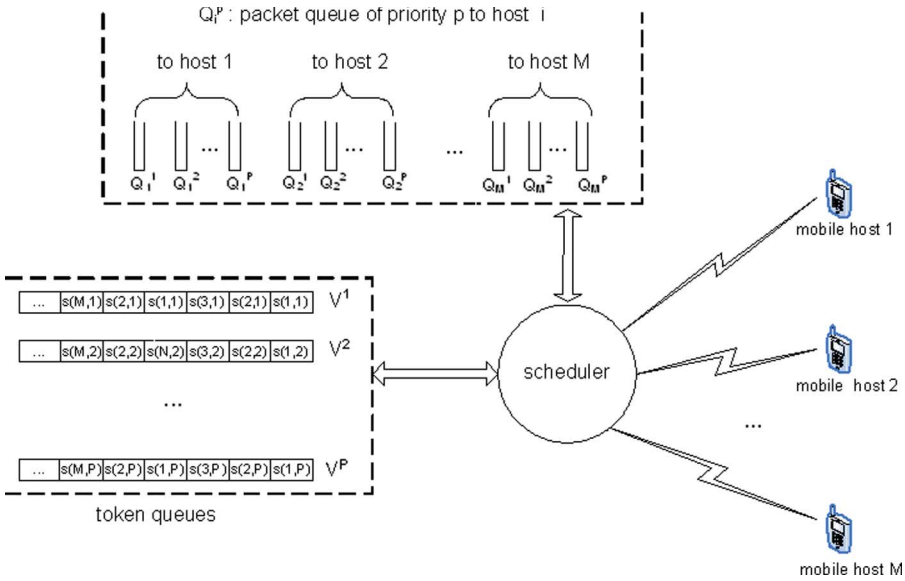


Fig. 2. Overall structure of OSBM.

In general, the QoS requirement of a flow is specified on a per-class basis, and we use a triple $(\sigma^p, \rho^p, D^p_{\max})$ to describe a class p traffic, where $D^p_{\max}$ is the end-to-end delay requirement of a priority p traffic. Considering the maximum delay D^p imposed by the core network, $\hat{D}^p = D^p_{\max} - D^p$ is the delay budget of the WPS algorithm in the base station for a priority p packet.

III. OSBM

The overall structure of the OSBM algorithm is illustrated in Fig. 2. The main components of OSBM include a set of packet queues, a set of token queues, and a priority-based scheduler. All the flows of priority p to host i are classified into group G^p_i $(i \in \{1, 2, \ldots, M\},\ p \in \{1, 2, \ldots, P\})$. OSBM maintains a separate packet queue Q^p_i for group G^p_i, as shown in Fig. 2. In addition to the packet queues, a token queue V^p $(p \in \{1, 2, \ldots, P\})$ is maintained for the transmission requests from group G^p, which is shared by all the flows of priority p regardless of the destination host of the flows. In Fig. 2, the token $s(i, p)$ in the token queue corresponds to a request to transmit a packet from queue Q^p_i. When a packet belonging to G^p_i arrives, it is inserted at the end of the packet queue Q^p_i. At the same time, a token $s(i, p)$ is created with the tag (host identification i, priority p) and inserted to the end of the token queue V^p.

When a packet is to be selected for transmission, the token queues are examined from the highest priority to the lowest priority. The nonempty token queue with the highest priority is identified, and the head-of-line token s is dequeued. From the tag (i, p) of s, the corresponding real packet queue Q^p_i is located, and its head-of-line packet is considered for transmission. After a packet is identified, two rules are applied to integrate channel quality information into the schedule: 1) Examine the channel quality before sending out a packet, and 2) check the delay of a real-time packet before transmission. The details of the two rules are described later in this paper.

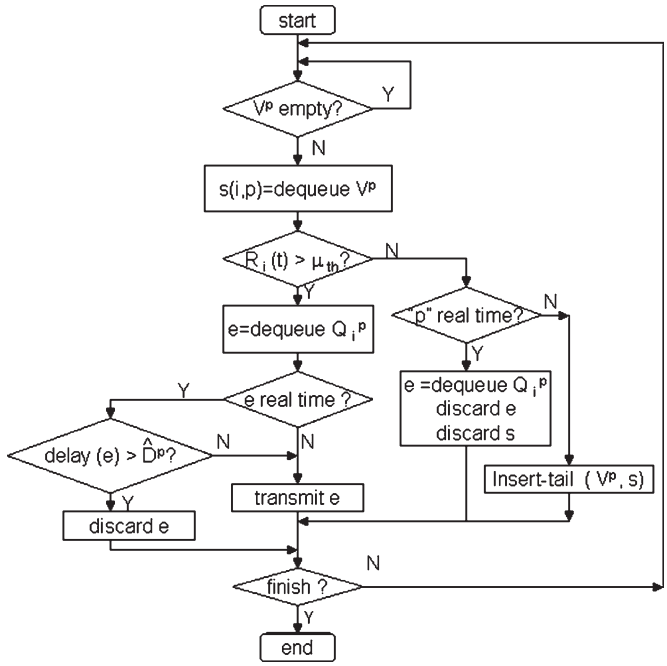


Fig. 3. Flowchart of OSBM packet dispatch operation.

As shown in Fig. 3, if the channel quality is bad and the packet is a real-time packet, the packet and the corresponding token are discarded. However, if the channel quality is bad and the packet is a nonreal-time packet, OSBM defers the transmission of the packet by inserting the corresponding token to the end of the same token queue without processing the real packet queue. The next token in the token queue is considered for transmission instead. This operation repeats until a packet with good channel quality is found. As a result, the time slot is assigned to a flow that observes a better channel quality, and the packet order is maintained at the output of the OSBM scheduler.

If the channel quality is good (Fig. 3), a nonreal-time packet is immediately sent out over the wireless link. However, if the packet is a real-time packet, the packet delay is examined to see

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if the accumulated packet delay is within the delay requirement stated in the service level agreement. If so, the real-time packet is transmitted; otherwise, the packet and the corresponding token are discarded. The purpose of this proactive packet discard mechanism is to improve the overall link throughput, and the effect of this action is demonstrated by the simulation results in Section V. To calculate the packet delay, a real-time packet is time stamped when it enters the scheduler, and an estimation of the delay imposed by the core network is provided beforehand.

The packet dispatch operation of OSBM is summarized in the flowchart in Fig. 3, where V stands for the set of token queues, and e stands for a data packet. In the test ("p" real time?), the priority "p" indicated by the token is examined to determine if the packet represented by token $s(i,p)$ is real time or not.

IV. Performance Analysis of OSBM

In this section, the delay bound of the OSBM algorithm is investigated. We propose a new concept of EDC, which approximates the long-term available data rate over the wireless link based on the statistics of the wireless channel. Using this concept, the service curve method for deterministic QoS analysis can now be applied in performance analysis for networks involving wireless links. The explicit expression of the delay bound of the OSBM algorithm is then obtained using the new analysis method.

A. Delay Bound of the OSBM Algorithm

EDC: The uncertainty of the wireless downlink capacity makes it difficult to directly apply the service curve analysis method to wireless links. To solve this problem, we propose the following concept of EDC.

Definition 1: Suppose μ_k is the smallest available channel rate that is not less than the threshold $\mu_{\rm th}$, i.e., $\mu_{k-1} < \mu_{\rm th} \leq \mu_k$ $(k \in \{1,2,\ldots,K\})$, where $\mu_{\rm th}$ is the channel threshold used in the OSBM algorithm, and $\boldsymbol{\mu} = \{\mu_1,\ldots,\mu_K\}$ $(\mu_1 < \mu_2 < \cdots < \mu_K)$ is the set of discrete available channel rates in the packet cellular network, the EDC $\bar{R}$ is defined as

$$\bar{R} = \alpha \sum_{i=k}^{K} p_i \mu_i \tag{4}$$

where p_i is the probability that a host's feasible data rate is μ_i, and α is a constant with a positive value that is used to adjust the value of $\bar{R}$.

We understand that most of the time, the service rate of the scheduling system is between $\mu_{\rm th}$ and μ_K. Therefore, the EDC in Definition 1 is the expected service rate adjusted by the constant factor α. $\alpha = 1 \pm \zeta$ (ζ being a small positive value) is a value close to 1, and we use $\alpha = 1$ in our simulation experiment. In the aforementioned definition, we assume that all mobile nodes randomly move at a random speed in the cell; thus, the channel rate distribution is the same for all mobile hosts.

Delay Bound for Real-Time and Nonreal-Time Packets: Consider a stable OSBM system for real-time packets that are successfully dispatched by the OSBM algorithm. The maximum delay $d^p_{\max}$ for a priority p $(p \leq P')$ packet is

$$d^p_{\max} = \hat{D}^p, \qquad p \in \{1,2,\ldots,P'\} \tag{5}$$

where $\hat{D}^p$ is the delay threshold used in the OSBM algorithm for priority p real-time flows.

This is easy to understand because before OSBM schedules a real-time packet, it first examines the queuing delay of the packet. If the queuing delay is longer than the threshold $\hat{D}^p$, the packet is discarded. Only the packet with a queuing delay less than or equal to the threshold is successfully dispatched over the wireless link. Therefore, the conclusion in (5) is true.

For a nonreal-time packet of priority p $(P' < p \leq P)$, the maximum delay is given in the following theorem.

Theorem 1: If traffic flows are regulated at the network entrance by a leaky bucket with parameters (σ^j, ρ^j) $(j \in \{1,2,\ldots,P\})$ for a priority j flow, the maximum delay $d^p_{\max}$ $(p \in \{P'+1,\ldots,P\})$ of a nonreal-time packet with priority p is given by

$$d^p_{\max} = \frac{\sum_{q=1}^{p-1} n^q(\eta^q + \rho^q\tau) + n^p(\eta^p + \rho^p\tau) - \bar{R}\tau}{\bar{R} - \sum_{q=1}^{p-1} n^q\rho^q} \tag{6}$$

where

$$\tau = \max\left\{0, \frac{\eta^p - \beta^p}{C - \rho^p}\right\} \tag{7}$$

and $n^j = \sum_{i=1}^{M} n_i^j$ $(j \in \{1,2,\ldots,p\})$, in which n_i^j is the number of flows in group G_i^j. $\eta_j = \sigma^j + \rho^j D^j$ $(j \in \{1,2,\ldots,p\})$, in which D^j is the maximum packet delay imposed by the core network for a priority j flow, and $\bar{R}$ is as given in Definition 1.

Proof: Considering a busy period $[0,T_b)$, under the condition that no packet is discarded by the OSBM algorithm, the delay $\tilde{d}^p(t)$ experienced by a nonreal-time priority p packet at time $t \in [0,T_b)$ can be formulated as

$$\tilde{d}^p(t) = \inf\left\{\tau \geq t : S(0,\tau) = \sum_{q=1}^{p-1} A^q(0,\tau) + A^p(0,t)\right\} - t \tag{8}$$

where $p \in \{P'+1,\ldots,P\}$, $S(t_1,t_2)$ is the total amount of data transmitted over the wireless link during the time interval $[t_1,t_2)$. $A^q(t_1,t_2)$ is the amount of traffic arrival from group G^q (Section II-B) during the time interval $[t_1,t_2)$. Equation (8) indicates that the waiting time of a packet with priority p includes the time to transmit all the existing packets of higher or equal priority that have arrived earlier and the time to transmit all the packets with higher priority that arrive during the queuing time of the priority p packet. In OSBM, some real-time packets may be discarded due to a violation of the

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delay requirements; therefore, the delay $d^p(t)$ of a nonreal-time packet of priority p is less than $\tilde{d}^p(t)$, i.e.,

$$d^p(t) \le \tilde{d}^p(t) = \inf\left\{\tau \ge t : S(0,\tau) = \sum_{q=1}^{p-1} A^q(0,\tau) + A^p(0,t)\right\} - t. \tag{9}$$

Using the concept of EDC in Definition 1, the maximum delay of a priority p packet is obtained by substituting the arrival function $A^j(t_1,t_2)$ $(j \in \{1,2,\ldots p\})$ with the traffic constraint function $F^j(I)$ $(j \in \{1,2,\ldots,p\})$ [18], i.e.,

$$d^p_{\max} = \frac{1}{\bar{R}} \max_{I<T_b} \left(\hat{F}^p\left(I + d^p_{\max}\right) - \bar{R}I\right) \tag{10}$$

where

$$\hat{F}^p\left(I + d^p_{\max}\right) = \sum_{q=1}^{p-1} F^q\left(I + d^p_{\max}\right) + F^p(I) \tag{11}$$

$$T_b = \min\left\{I > 0 : \sum_{q=1}^{p} F^q(I) \le \bar{R}I\right\}. \tag{12}$$

The maximum delay $d^p_{\max}$ in (10) depends on the traffic constraint function $F^j(I)$ $(j \in \{1,2,\ldots,p\})$ at the base station. Since the traffic is regulated at the ingress node, the burstiness of the flow accumulates as the packets travel downstream along the path. When packets arrive at the base station, the arrival pattern can no longer be described by the source constraint function $H^j_x(I)$ $(j \in \{1,2,\ldots,p\})$. However, if the maximum delay imposed by the core network is predictable, using a technique in [18], $F^j(I)$ at the base station can be expressed using the source traffic constraint function $H^j_x(I)$ (see Fig. 1). For flow x of priority j, the following holds:

$$F_x(I) \le H^j_x(I + D_x) \le H^j_x(I + D^j) \tag{13}$$

where $H^j_x(I) = \min\{CI, \sigma^j + \rho^j I\}$, as defined in Section II-B, D_x is the maximum packet delay of flow x imposed by the core network, and D^j is the maximum delay of all priority j packets imposed by the core network. Since all priority j flows have the same source constraint function $H^j_x(I)$, the traffic constraint function for group G^j_i can be expressed as

$$\begin{aligned} F^j_i(I) &= \sum_{x \in G^j_i} F_x(I) \\ &\le \sum_{x \in G^j_i} H^j_x(I + D^j) \\ &= \min\left\{n^j_i(CD^j + CI), n^j_i(\sigma^j + \rho^j I + \rho^j D^j)\right\} \\ &= \min\left\{n^j_i(\beta^j + CI), n^j_i(\eta^j + \rho^j I)\right\} \end{aligned} \tag{14}$$

where n^j_i is the number of flows in group G^j_i, $\beta^j = CD^j$, and $\eta^j = \sigma^j + \rho^j D^j$. The traffic constraint function for group G^j can be expressed as

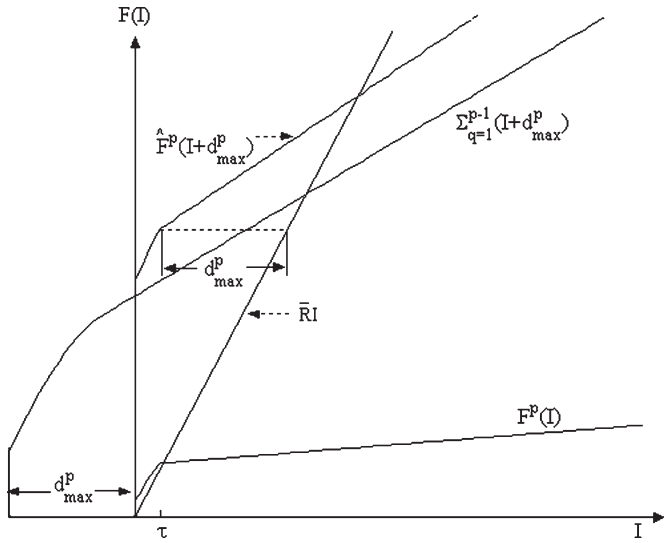


Fig. 4. Delay bound for a nonreal-time packet.

$$\begin{aligned} F^j(I) &= \sum_{i=1}^{M} F^j_i(I) \\ &\le \min\left\{\sum_{i=1}^{M} n^j_i(\beta^j + CI), \sum_{i=1}^{M} n^j_i(\eta^j + \rho^j I)\right\} \\ &= \min\left\{n^j(\beta^j + CI), n^j(\eta^j + \rho^j I)\right\} \end{aligned} \tag{15}$$

where $n^j = \sum_{i=1}^{M} n^j_i$. As illustrated in Fig. 4, $F^j(I)$ $(j \in \{1,2,\ldots,p\})$ is a two-segment linear function under the assumption that all priority j flows are subject to the same source constraint function $H^j_x(I)$. The joining point of the two segments is called a flex point. For the constraint function $F^j(I)$, the flex point τ^j is

$$\tau^j = \max\left\{0, \frac{n^j\eta^j - n^j\beta^j}{n^jC - n^j\rho^j} = \frac{\eta^j - \beta^j}{C - \rho^j}\right\}. \tag{16}$$

Applying (15) into (11), we can obtain the explicit expression of $\hat{F}^p(I + d^p_{\max})$. To obtain the explicit expression of $d^p_{\max}$, we need to find the point where the worst-case delay in (10) occurs. Note that the flex points of $F^j(I)$ $(j \in \{1,2,\ldots,p-1\})$ are also the flex points of the function $\sum_{q=1}^{p-1} F^q(I)$ in (11). The aggregated constraint function $\hat{F}^p(I + d^p_{\max})$ in (11) includes the following two parts: 1) the aggregated traffic constraint function with priorities higher than p, denoted by $\sum_{q=1}^{p-1} F^q(I + d^p_{\max})$, which does not have any flex points for $I \ge 0$ as proven in [18]; and 2) the traffic function with priority p, denoted by $F^p(I)$, which has a single flex point $\tau^p = \max\{0, (\eta^p - \beta^p)/(C - \rho^p)\}$. τ^p is also the flex point of $\hat{F}^p(I + d^p_{\max})$, and the maximum delay $d^p_{\max}$ occurs at $I = \tau = \tau^p = \max\{0, (\eta^p - \beta^p)/(C - \rho^p)\}$. The maximum delay $d^p_{\max}$ in (10) can thus be represented as follows using (15):

$$\bar{R}d^p_{\max} = \sum_{q=1}^{p-1} n^q\left(\eta^q + \rho^q\left(\tau + d^p_{\max}\right)\right) + n^p(\eta^p + \rho^p\tau) - \tau\bar{R}. \tag{17}$$

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TABLE I
PERFORMANCE COMPARISON BETWEEN IWFQ, WCFQ, AND OSBM

	IWFQ	WCFQ	OSBM
delay guarantee	$\bar{D}_{HOL,e} \leq \bar{D}_{HOL,WFQ,e} + T_{e,(M+1)}$ [a]	no explicit guarantee	$d^p_{max} = \hat{D}^p, \quad p \in \{1, 2, ..., P'\}$ (for real time flows) $d^p_{max} = \frac{\sum_{q=1}^{p-1} n^q(\eta^q+\rho^q\tau)+n^p(\eta^p+\rho^p\tau)-\bar{R}\tau}{\bar{R}-\sum_{q=1}^{p-1} n^q\rho^q}$ (for non-real-time flows)
fairness	similar to WFQ	$Pr(\lvert\frac{\alpha_i(t_1,t_2)}{\phi_i} - \frac{\alpha_j(t_1,t_2)}{\phi_j}\rvert \geq \frac{L_i^{max}+x}{\phi_i} + \frac{L_j^{max}+x}{\phi_j}) \leq Pr(\frac{U_i(p_i')}{\phi_i} + \frac{U_j(p_j')}{\phi_j} \geq \frac{x}{\phi_i} + \frac{x}{\phi_j})$ [b] (similar to CBFQ)	similar to static priority (SP)
service differentiation	No	No	yes
complexity	O(log(n)) [c]	O(J) [d]	O(1)

[a] $\bar{D}_{HOL,WFQ,e}$ is the new queue delay under error-free WFQ, M is the minimum number of lagging slots of all flows other than flow e, and $T_{e,(M+1)}$ is the maximum time it takes for flow e to have its $(M+1)th$ good slot starting from any time t. [12]

[b] $\alpha_i(t_1, t_2)$ is the service in time that flow i receives during (t_1, t_2), ϕ_i is the weight of flow i, $U_i(p)$ is the estimated cost for user i to transmit the pth packet, L_i^{max} is the maximum packet length of flow i. [13]

[c] n is the total number of packets in the system

[d] J is the total number of flows in the system

By rearranging (17), we have

$$d^p_{\max} = \frac{\sum_{q=1}^{p-1} n^q(\eta^q + \rho^q\tau) + n^p(\eta^p + \rho^p\tau) - \bar{R}\tau}{\bar{R} - \sum_{q=1}^{p-1} n^q\rho^q} \quad (18)$$

and the result in Theorem 1 is proven. ■

Theorem 1 explicitly gives the delay bound for a nonreal-time packet provided by the OSBM scheduling algorithm. The delay bound is closely related to the population of flows (n_i^j), the leaky bucket parameters ρ^j and σ^j, the delay imposed by the core network, and the EDC $\bar{R}$. Given the required end-to-end delay $D^p_{\max}$, and the estimated delay in the core network D^p, (6) may also be used to control the number of flows of each priority that can be admitted in the network.

B. Comparison With the Existing Scheduling Algorithms

Table I shows the features of OSBM, the idealized wireless fair queuing (IWFQ) [12], and the wireless credit-based fair queuing (WCFQ) [13]. IWFQ and WCFQ are chosen as the benchmark algorithms because they are well known and they tackle the same scheduling problem over wireless downlink as OSBM does. From the table, it can be seen that OSBM is a simple yet effective scheduling algorithm compared with the other two algorithms.

V. NUMERICAL RESULTS

In this section, we present the simulation experiments conducted to compare the performances of WCFQ, IWFQ, and the proposed OSBM scheduling schemes. For illustration purposes, the cost functions in WCFQ are set to generate an infinite discrepancy under different channel conditions [13]. In other words, WCFQ simply selects the user with the best channel in this experiment. On the other hand, since a direct implementation of the IWFQ algorithm is not realistic, and the authors of [12] have proposed the WPS algorithm to approximate the idealized IWFQ algorithm while addressing several implementation issues, we have chosen to implement the WPS algorithm instead of IWFQ and compare the performances between WCFQ, WPS, and OSBM. In addition, we have implemented the conventional static priority queuing (SPQ) algorithm as a benchmark that does not consider the quality of the wireless channel in the scheduling process. The experiments are done using ns-2 [21], and the network configuration in this simulation is shown in Fig. 5.

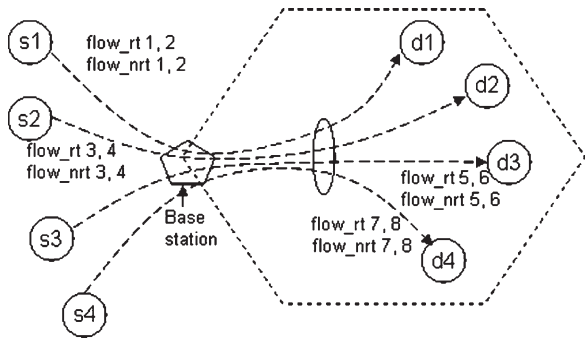


Fig. 5. Network configuration of the simulation experiments.

As shown in Fig. 5, four mobile hosts (i.e., d1, d2, d3, and d4) share the wireless downlink from the base station. Between each of the four source–destination pairs (i.e., s1–d1, s2–d2, s3–d3, and s4–d4), four communication sessions are established, including two real-time sessions and two nonreal-time sessions. Real-time traffic sources in Fig. 5 are constant bit rate traffic provided by ns-2. Nonreal-time traffic sources are exponential traffic provided by ns-2. The total input traffic load is adjusted by tuning the interpacket interval and the average

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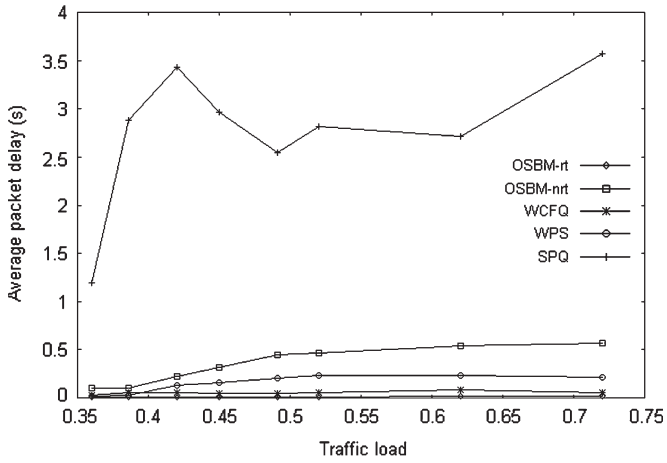


Fig. 6. Average packet delay versus traffic load.

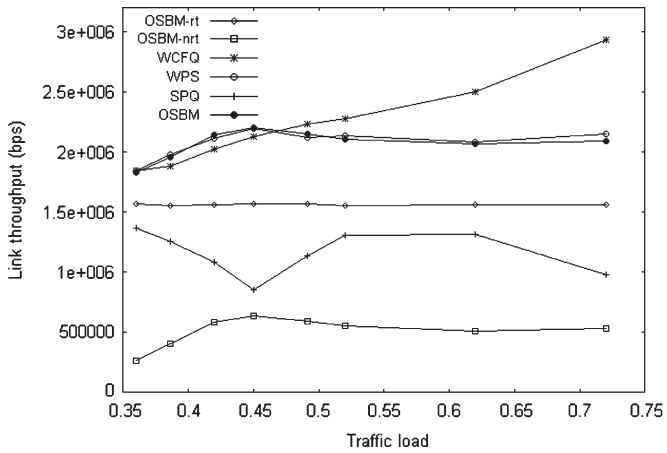


Fig. 7. Link throughput versus traffic load.

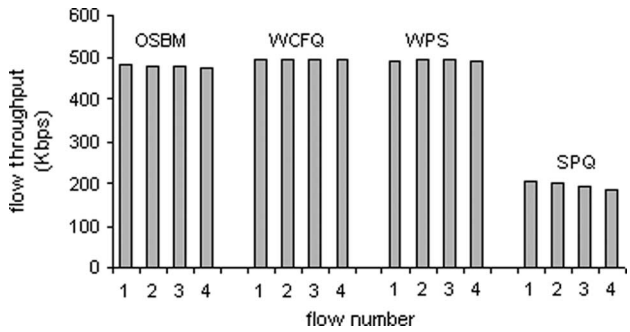


Fig. 8. Throughput of individual flows.

packet size. The buffer size is set to 200 packets for all of the four scheduling schemes, and the other parameters for OSBM are as follows: delay threshold is 100 ms for real-time packets, and the channel threshold is $\mu_{\rm th} = 1.3\,\mu_1$. WCFQ, WPS, SPQ, and the proposed OSBM scheduling schemes are respectively implemented by the base station, and the performances of the algorithms are compared in terms of the average packet delay, link throughput, and fairness, as shown in Figs. 6–8.

Fig. 6 shows the average packet delay as a function of the traffic load when OSBM, WCFQ, WPS, and SPQ schedulers are, respectively, used. The advantage of channel-aware scheduling algorithms (i.e., OSBM, WCFQ, and WPS) is obvious because their average packet delay is much lower than that of SPQ. In this figure, the average packet delay for OSBM real-time sessions is very low, even when the traffic load is heavy. By contrast, the average packet delays for WCFQ and WPS are much longer than that for OSBM in most traffic conditions.

Fig. 7 shows the link throughput achieved by OSBM, WCFQ, WPS, and SPQ, respectively, where the link throughput is defined as the total number of data bits that are delivered to the destination. In general, the link throughput achieved by channel-aware schedulers (i.e., OSBM, WCFQ, and WPS) is much better than that of SPQ. Among the three channel-aware schedulers, OSBM and WPS have similar throughput. WCFQ achieves a better throughput than WPS and OSBM but at the cost of starvation of users with constant poor channels [12].

To keep the implementation simple, OSBM provides priority-based sharing of the wireless bandwidth. However, for flows within the same priority, OSBM does not have explicit fairness rules; therefore, the bandwidth is shared by users within the same priority based on the traffic arrival pattern. As a result, admission control and traffic policing are necessary to make sure that no malicious user is allowed to send excess packets to deplete the link bandwidth. Fig. 8 illustrates that well-controlled users at the same priority level can fairly share the link bandwidth in the OSBM, WCFQ, and WPS schedulers.

From the aforementioned observation, we can conclude that OSBM performs well in adapting to the changing channel conditions of the wireless link. It is able to provide differentiated services to real-time and nonreal-time applications in terms of packet delay. Compared with WCFQ and WPS, OSBM is easy to implement and is more suitable for applications where prioritized services must be provided.

VI. Conclusion

In this paper, OSBM is proposed to provide differentiated services to support real-time and nonreal-time applications. The OSBM algorithm uses a novel queue management technique to accommodate the changing channel conditions and delay constraints of real-time data. A proactive packet discard mechanism is used to make more efficient use of the wireless channel. OSBM is a channel-state-dependent scheduling algorithm with provable delay bounds and reasonably high link throughput. More importantly, since OSBM involves no complex online computation, it is very efficient and easy to implement in an operational environment.

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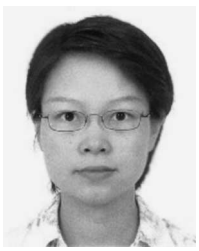
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