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A unified bandwidth reservation and admission control mechanism for QoS provisioning in cellular networks

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Summary

We propose a unified framework consisting of a differential bandwidth reservation (DBR) algorithm and a Quality of Service (QoS)-aware admission control scheme to provide QoS guarantees to on-going connections in cellular networks. The differential bandwidth reservation policy uses a sector of cells in making the bandwidth reservation for accepting a new call. Based on the distance of the target cells in the sectors, two different bandwidth reservation policies are applied to optimize the connection dropping rate (CDR), while maintaining a competitive connection blocking rate (CBR). In addition, two possible mobile terminal (MT) movements are analyzed using the DBR mechanism. In the first case, no knowledge of an MT's moving path is assumed to be known, while in the second case, prior knowledge of an user profile is used in bandwidth reservation, and it is called user profile-based DBR (UPDBR) algorithm. Using the DBR scheme, we propose an admission control algorithm that uses varying number of cells in a sector to meet admission decisions. Extensive simulation is performed to evaluate our methodology. Comparison of the proposed scheme with two prior schemes shows that our approach is not only capable of providing better QoS guarantees, but is also flexible in terms of using varying number of cells in satisfying the high-level QoS requirements. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: cellular networks; admission control; quality-of-service; differential bandwidth reservation; handoff

1. Introduction

As cellular networks are envisioned to be a ubiquitous communication infrastructure that will include a variety of mobile devices, provisioning of seamless communication as well as Quality-of-Service (QoS) guarantees to on-going and new connections are critical issues in designing such networks. Since a myriad of multimedia applications are expected to be serviced by cellular networks, managing the limited resources in a mobile environment brings in new design challenges. Specifically, due to the movement of users during communication sessions, one of the most important QoS factors is related to handoff. A handoff, however, could fail due to unavailability of sufficient bandwidth in the destination cell. As the

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number of mobile terminals (MTs)[‡] increases, the probability of connection handoffs, and hence being dropped due to insufficient bandwidth during the lifetime of a connection could be high.

Connection dropping rate (CDR) can be reduced by reserving some bandwidth solely for handoffs. However, the connection blocking rate (CBR) of new connections may increase due to such bandwidth reservation. Hence, reduction of CBR and CDR are conflicting requirements, and optimization of both is admittedly extremely complex. Two supplementary techniques have been used for controlling the CDR and CBR in cellular networks—bandwidth reservation and admission control. While bandwidth reservation helps in minimizing the CDR of on-going connections, it cannot effectively guarantee a certain level of QoS without an admission control scheme when the traffic load is high. The difficulty in admission control in a mobile environment is that it is not adequate to admit a new call only based on the status of the current cell, where the call is generated. This is because when the MT attempts to move from the original cell to a next cell, there may not be sufficient bandwidth in the destination cell for accepting the handoff. This may result in dropping the call and increasing the CDR. Therefore, an efficient admission control policy should check the bandwidth availability in the adjacent cells for a smooth handoff. Although dropping the handoff of an on-going connection is considered more objectionable than blocking a new connection, designing a system with zero CDR is practically impossible. Hence, most admission control policies attempt to provide an acceptable CDR, called target QoS for CDR or T_{QoS}, of 1 or 2%.

Most prior bandwidth reservation schemes [13,21] were based on handoff prioritization, where each cell reserves a fixed bandwidth or dynamically adjustable amount of bandwidth exclusively for handoffs. Other prioritizing schemes [11,29] either allow the handoffs or new connections to be queued until enough bandwidth is available in a cell. Also, several distributed channel allocation algorithms have been proposed to increase channel reuse to meet the increasing demand for wireless communication [5,9]. In these studies, a new connection is blocked when a base station (BS) does not have available bandwidth or cannot borrow a channel from neighboring BSs. These schemes do not use any explicit admission control for satisfying a given QoS. Recently, a dynamic channel allocation scheme is integrated with an adaptive handoff mechanism [4] to improve the bandwidth utility and guarantee a certain level of QoS. However, the dynamic channel allocation schemes incur high message complexity when traffic load is high.

Instead of only considering the current cell, where a new connection is initiated, admission control schemes [3,16,19] consider the status of a number of cells, which are located around or along the path in which the MT might move, and then make an admission decision based on the agreement among all cells or a subset of cells respectively. For example, Naghshineh and Schwartz [19] suggested a distributed admission control scheme, where the current cell and all its immediate adjacent cells are considered to decide whether a new connection should be accepted or not. The shadow cluster concept introduced in Reference [16] estimates the future resource requirements and considers a set of cells located around an active MT. However, these schemes are based on strong assumptions such as precise knowledge about handoff and connection termination, as well as the MT's mobility pattern. Aljadhai and Znati [3] defined a most likely cluster (MLC), which is a set of cells to which an MT is likely to move with a higher probability during its lifetime. The shape of the MLC and the number of cells in the MLC are determined based on the moving speed and direction of the MT. Since all cells or a fraction of the cells in the MLC need to reserve bandwidth before admitting a new connection, the approach may either waste a large amount of bandwidth or may not well adapt to the T_{QoS}.

To keep the CDR below a predefined level, several bandwidth reservation schemes have been suggested using effective prediction mechanisms [6,8,10,26,31]. The global positioning system (GPS) technology [22] can be used to provide accurate position, velocity and direction of an MT in real time. It is already commercialized and installed on a wide range of devices such as cellular phones, personal digital assistants (PDA) and wireless interface cards. Chiu and Bassiouni [6] and Sho and Kim [26] proposed to predict an MT's moving direction and reserve bandwidth dynamically based on the accurate handoff prediction. To increase the accuracy of an MT's mobility, the size of GPS units is kept small. In addition, these techniques require frequent communication between an MT and the satellite. An aggregated moving history of an MT is used to estimate the MT's handoff behavior [8]. Based on the prediction, the number of reserved bandwidths is calculated. This scheme also incurs

[‡]In this paper, we use the term mobile terminal (MT) to refer to a portable device or a person who carries it.

high communication overhead for providing accurate prediction of an MT's movement.

Similar resource reservation and admission control schemes [15,18,28] have been applied to packet-switched cellular networks to provide QoS support for high-speed multimedia applications such as video conferencing, digital library and video-on-demand (VOD). Lu *et al.* [18] proposed an adaptive QoS design scheme based on a revenue-based resource adaptation and bandwidth reservation, where the next cell prediction for handoff was deployed. Talukdar *et al.* [28] suggested an admission control, derived from a measurement-based admission control scheme [12], to increase utilization of resources for real-time applications.

In most prior studies, bandwidth reservation and admission control have been treated orthogonally. However, it is essential to combine both these techniques to provide improved and predictable performance in cellular networks. Our paper proposes such an integrated approach. We propose a differential bandwidth reservation (DBR) scheme that uses a sector-type configuration to reserve/share bandwidth along the path of an MT. The size of the sector and the number of cells in the sector can be dynamically configured for each MT using its mobility information. The sector of cells are further divided into two regions, called inner and outer sectors depending on whether they have an immediate effects on the handoff or not. While bandwidth reservation is used in the inner sector, bandwidth sharing is used in the outer sector to improve the effectiveness of resource sharing. We enhance the performance of the DBR algorithm with a user profile-based DBR (UPDBR) policy that relies on the known mobility pattern of the MTs for better path prediction.

In addition, a QoS-aware admission control scheme using the differential bandwidth reservation policy is proposed. The admission control algorithm first uses the bandwidth reservation algorithm to check if bandwidth reservation can be done in appropriate cells to admit the new call. In contrast to most prior schemes, not all the cells in the sector are required to reserve or share the bandwidth for satisfying the QoS requirement. The number of cells involved in admission control can be changed dynamically depending on the average CDR of the cells in the sector and that of the current cell, where a new connection is generated. The novelty of the proposed admission control mechanism is that it is adaptable to the mobility pattern of the MTs in terms of the sector size, number of cells in the sector and specific QoS parameters.

We simulate a (6×6) wrap-around network of hexagonal cells to evaluate the effectiveness of the proposed DBR and admission control mechanisms. We compare our integrated technique with two related schemes, called STATIC [21] and predictive timed QoS guarantees (PT-QoS), which is based on the MLC concept [3]. Both voice and data traffics are used for performance evaluation. Simulation results indicate that our scheme is more adaptable to provide a certain level of CDR guarantee compared to the prior schemes. In particular, it guarantees the specified CDR over the entire workload, while maintaining a competitive CBR. The UPDBR scheme can exploit the path history for better bandwidth utilization as well as reduction in the number of communication messages compared to the DBR. In addition, we study the impact of the cell size, the number of cells involved in making admission decisions and other system parameters in satisfying the overall QoS parameters.

The rest of this paper is organized as follows. We introduces the system model in Section 2. Also, the proposed bandwidth reservation and admission control policy are presented. Section 3 is devoted to performance evaluation and comparisons of the algorithms. Finally, Section 4 concludes the paper.

2. A Unified Bandwidth Reservation and Admission Control Mechanism

In this section, first we present the system model, where a set of cells is divided into a couple of clusters in the form of a sector. Based on this model, we propose a DBR policy and then an admission control scheme that utilizes the DBR scheme.

In the proposed DBR approach, two different reservation policies are applied to two different regions of cells in the sector, $R(\theta)$. All cells in the sector participate in bandwidth reservation, and a new connection is accepted only if the current cell has enough available bandwidth and all (or part of) participating cells are ready to reserve or share the bandwidth. In addition, we consider the known mobility pattern of the MTs for better path prediction in implementing the differential bandwidth reservation policy.

The proposed admission control mechanism attempts to keep the CDR below a target QoS value by judiciously using our bandwidth reservation algorithm. A BS is assumed to have some knowledge of the moving pattern of a new call. Using this information, the BS checks if a new bandwidth reservation in the appropriate cells can be done to accommodate the new call.

2.1. System Model

In cellular networks, each cell is supported by a BS located in the center of the cell. The BSs are connected to each other by a static wired network. Each MT in a cell communicates with the BS by wireless links. Each cell is assigned a fixed number of channels (or bandwidth). An MT may make a connection request from anywhere in any cell. Since an MT tends to keep its original moving direction, it has a lower probability of making a sudden turn compared to maintaining the current direction. Therefore, let us assume that an MT moves straight, left, right, lower left, lower right and back with probabilities of P_S, P_L, P_R, P_{LL}, P_{LR} and P_B respectively. Further, we assume that the MT moves with a constant speed in a cell and changes (or may not change) direction at the cell boundary.

We assume that a BS is capable of predicting the direction of a new connection based on its path history, which is recorded at the MT. Typically, a BS periodically broadcasts control messages to the MTs in its area for location and bandwidth management. A BS's *id* consisting of a few bits can be easily added to the control message without much overhead. Usually, an MT stays in the power-saving mode to reduce battery consumption when it is idle. However, it still listens to the control channel. Whenever the MT moves into a new cell, it identifies the BS *id* using control messages, and caches the *id* in its memory. When the MT makes a new call, it sends the list of *ids* with the connection request message to the BS. The BS can predict the next cell to which the MT might move from the path (*id*) list. Similar assumptions have been used in prior research [3,27]. More accurate moving directions can be obtained by using the GPS [22].

Since an MT has a much higher probability of maintaining its current direction, or moving left, or moving right than the other three directions, there exists a sector of cells covered within an angle (θ) to which the MT might move in the near future. This is similar to the MLC concept [3]. This sector of cells can be classified based on their distance from the current cell. Let $r_{i,d}$ denote the cluster of cells located at a distance[§] d to which the MT might move with a higher probability from the current cell c_i. Let $R(\theta)$ denote the sector of cells located within θ. Then, we have:

$$r_{i,d} = \{c_j | \mathcal{N}(\text{distance}(c_i, c_j)) = d \wedge c_j \in R(\theta)\},\quad \text{where } d = 1, 2, \ldots, n. \tag{1}$$

As shown in Figure 1, cluster $r_{i,1}$ consists of three cells, c_1, c_2 and c_3, while cluster $r_{i,4}$ has seven cells, c_{12}–c_{18}. As the distance d increases, the number of cells in that cluster increases. Depending on the moving speed and mobility pattern of MTs, the number of cells in a cluster and the maximum cluster distance n should be carefully chosen. Also, the sector angle θ is likely to affect the system performance. For the sake of simplicity, we assume that all the cells in the sector are under the same switch such as a mobile station center (MSC), as used in Reference [20].

2.2. A Differential Bandwidth Reservation Algorithm

Bandwidth reservation is essential for seamless handoff of an MT from one cell to the next cell. When making bandwidth reservations, it is more effective to consider a cluster of cells, which includes cells located around or along the way to which the MT might move. Furthermore, there should be different bandwidth reservation policies for different cells depending on their distance from the current cell. For example, suppose an MT in a cell c_i is likely to perform a handoff. BS_i can predict the direction in which the MT might move based on the path history of the MT and then construct a sector of cells for the bandwidth reservation. It is easy to see that the MT will most likely move to the cells closer to c_i, such as the cells in $r_{i,1}$ and $r_{i,2}$ in Figure 1. Since the MT may change its direction at any time, it has a relatively lower probability of moving to cells located far away from the cell c_i, such as the cells in $r_{i,4}$. Based on this observation, for each cell c_i, cells that are required for bandwidth reservations are classified into two different regions: $R_I(i)$ and $R_{II}(i)$.

- $R_I(i)$: It contains the cells located closer to c_i. For example, cells in $r_{i,1}$ and $r_{i,2}$ are close to c_i and they have a direct impact on CDR because the handoff will fail if the requested bandwidth is not available.
- $R_{II}(i)$: It contains the cells further away from c_i. For example, cells in $r_{i,3}$ and $r_{i,4}$ are three and four cell distant away from c_i, and they only have indirect effects on the handoff because the MT may not move to those cells.

[§]In this paper, we use distance (d) as the normalized distance, $\mathcal{N}$ (distance(c_i, c_j)), between the current cell (e.g. c_i), where the MT is located and the center of the other cell (e.g. c_j).

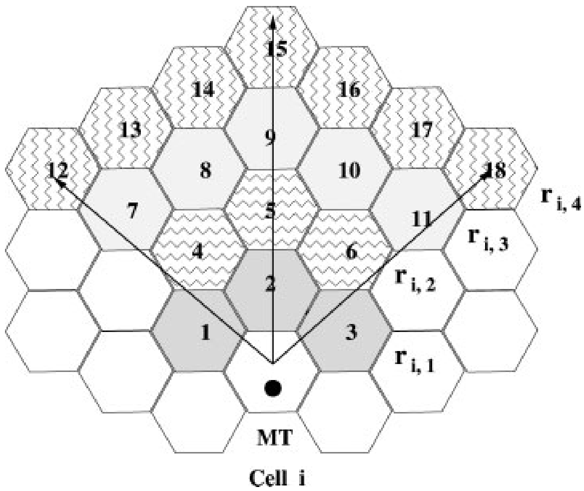


Fig. 1. Classification of sector of cells into different clusters based on their distance from the current cell.

These regions are referred to as inner and outer regions respectively. For each handoff request, a BS reserves or shares bandwidth of the cells in both regions. Since several BSs could request reservations for the corresponding handoff requests, a cell c_m may be involved in multiple reservations from different BSs. As an example, consider two handoff requests from two cells c_i and c_j. BS_i and BS_j make bandwidth reservations in their corresponding regions of cells; i.e. $R_I(i)$ and $R_{II}(i)$, and $R_I(j)$ and $R_{II}(j)$. As a result, c_m can be included in $R_I(i)$ or $R_{II}(i)$, and in $R_I(j)$ or $R_{II}(j)$. In this case, c_m reserves bandwidth for handoff requests from c_i and c_j. The differential bandwidth reservation policies for the two regions (inner and outer) are described next.

Prior to initiating a handoff, BS_i first constructs the sector configuration and broadcasts the region information along with the reservation request to the corresponding cells. When BS_m receives a handoff request from BS_i, it already knows its reservation region. If c_m is in $R_I(i)$, BS_m makes bandwidth reservation using the condition:

$$N_{\text{used}}(m) + \text{bw} \leq N_{\text{total}} - N_{\text{resv}}(m)$$

where $N_{\text{used}}(m)$ is the currently used bandwidth, bw is the requested bandwidth, N_{total} is the total bandwidth of the cell, and $N_{\text{resv}}(m)$ is the currently reserved bandwidth for handoffs. If the above condition is not satisfied, BS_m checks if it can share the already reserved bandwidth with other cells. For bandwidth sharing, the reserved bandwidth is not strictly assigned to any particular MT, and hence, can be used by any MT on a first-come-first-serve (FCFS) manner. To implement this idea, BS_m checks if the sum of $N_{\text{resv}}(m)$, bw and the existing shared bandwidth $(N_{\text{share},I}(m) + N_{\text{share},II}(m) \times \epsilon/\eta)$ is less than or equal to. times of $N_{\text{resv}}(m)$. Note that the shared bandwidth could be different in the inner and outer regions, and they are specified by two different terms. We use a weight factor (ϵ/η), which is less than 1.0 for $N_{\text{share},II}(m)$, because the MT has a lower probability of moving to this region. Here, ϵ is a system parameter, which enables BS_m to reserve more than the actually allocated bandwidth, i.e. $\epsilon \geq 1$ based on the QoS requirement of the system. If any of the two conditions (reservation/sharing) is satisfied, BS_m sends a positive reply (ack) to BS_i. Otherwise, the reservation request from BS_i is rejected.

If c_m belongs to $R_{II}(i)$, the reservation may waste a large amount of bandwidth since the MT may not move into c_m. Thus, only bandwidth sharing is applied in the outer region. Specifically, BS_m checks if the sum of $N_{\text{resv}}(m)$, bw, and the existing shared bandwidth, $(N_{\text{share},II}(m) + N_{\text{share},I}(m) \times \eta/\epsilon)$, is less than or equal to η times of $N_{\text{resv}}(m)$, and then decides whether it can share the bandwidth or not. In contrast to $R_I(i)$, we use a weight factor (η/ε), which is greater than 1.0 for $N_{\text{share},I}(m)$ due to its high probability of being used. Similar to ϵ, η is a system QoS parameter, and $\eta \geq 1$. Intuitively, η should be higher than ϵ to facilitate more sharing in the outer region. The pseudo code for the bandwidth reservation is given in Figure 2.

2.3. An User Profile-Based DBR Algorithm

We extend the DBR algorithm presented in Section 2.2 for MTs whose moving path is known *a priori*. We refer it to as a UPDBR algorithm.

Several researchers have used user profiles for better location and handoff managements [20,23–25]. Sen *et al.* [24] use profile information to optimize the location management cost. They consider individual user mobility patterns as well as connection arrival patterns, and apply them to determine the transition probabilities between location areas based on a long period of observation about the movements of each MT. Rudrapatna *et al.* [23] utilize a repetitive travel pattern of MTs such as daily commuters. A statistical bandwidth reservation policy is used for such MTs that may need high QoS. However, none of these studies consider the cell regions, and only use the current cell instead of a sector of cells. Intuitively, if the user profile of a set of MTs can be known, the DBR algorithm can be used more effectively, because


```
if (c_m ∈ R_I(i)) {
    if (N_used(m) + bw ≤ N_total - N_resv(m)) {
        send ack to allocate bandwidth to c_i;
        N_resv(m) = N_resv(m) + bw;     /* done only after getting confirmation from BS_i */
    }
    else {
        if (N_resv(m) + bw + N_share,I(m) + N_share,II(m) * ε/η ≤ N_resv(m) × ε) {
            send ack to share bandwidth to c_i;
            N_share,I(m) = N_share,I(m) + bw;     /* done only after getting confirmation from BS_i */
        }
        else
            send nack to c_i;
    }
}
else { /* c_m ∈ R_II(i) */
    if (N_resv(m) + bw + N_share,II(m) + N_share,I(m) * η/ε ≤ N_resv(m) × η) {
        send ack to share bandwidth to c_i;
        N_share,II(m) = N_share,II(m) + bw;     /* done only after getting confirmation from BS_i */
    }
    else
        send nack to c_i;
}
```

Fig. 2. The differential bandwidth reservation scheme used in c_m when it receives a reservation request from c_i.

the $|r_{i,d}|$ becomes small, and hence, the number of cells used in the DBR negotiation will be small. This in turn should reduce the communication overhead. In the following, we describe the UPDBR scheme.

In the UPDBR approach, most of the MTs choose their favorite paths, use them frequently whenever they move, and do not change the path unless otherwise required (e.g. the path of a daily commuter is typically fixed). Therefore, we can extract the mobility pattern from the user profile and use it to predict the moving paths of such MTs with better accuracy. For the UPDBR algorithm, we assume that there are two groups of MTs. One is a user profile-based group, denoted as G_f, and the other is a non-user profile-based group, denoted as $G_{\bar{f}}$. The MTs in the G_f group have predictable travel behavior, whereas MTs in the $G_{\bar{f}}$ group exhibit little predictable behavior. The cellular network has the most recent statistical data for each MT in the G_f group. An MT in the G_f group has a probability of Φ to follow the predicted path. Also, the user profile for a particular user in the UPDBR algorithm is assumed to be under the same switch¶ (MSC) as used in Reference [20]. When many switches are involved in retrieving the user profile, the proposed technique may incur a longer call set up

¶In current cellular network standards such as GSM and IS-41 [2,14], a number of BSs are connected to a base station controller (BSC). The BSC is connected to a MSC, which is attached to the public networks. Two databases, i.e. the visitor location register (VLR) and the home location register (HLR) are used to save information about the MTs. The VLR and HLR are connected to the MSC and public networks. These three entities communicate with each other by out-of-band signaling system number 7 (SS7) [14]. The user profile, information saved in the VLR and HLR, is a statistical set of data collected for each MT. The collected data record the MT's routes of movement, connection time and traffic environment based on daily, weekly and even monthly statistics. Once an MT makes a connection request, the corresponding BS initiates a search for the user profile through the BSC and MSC. The user profile, if available, is retrieved from the VLR or the HLR, and transmitted to the BS through the MSC and the BSC. Since the BS is transparent to the VLR or HLR from the MT's view, we use the terms BS, VLR and HLR interchangeably in this paper.

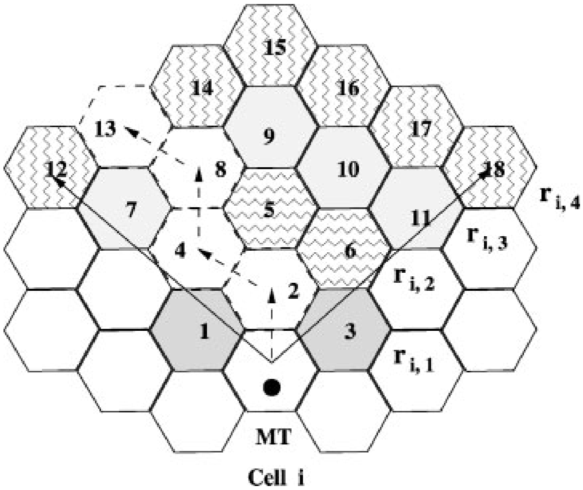


Fig. 3. An example of the user profile-based differential bandwidth reservation (UPDBR) policy. For the original DBR policy, all the cells starting from c_1 to c_{18} may participate in bandwidth reservation. Whereas in the UPDBR approach, only cells c_2, c_4, c_8 and c_{13} are involved in the bandwidth reservation.

delay. However, since the BSs are connected through high-speed networking, the setup delay may not be too high.

Whenever a new connection is generated in a cell c_i, BS_i checks whether the MT belongs to the G_f or $G_{\bar{f}}$ group. For bandwidth reservation, if the MT belongs to G_f, BS_i establishes $R_I(i)$ and $R_{II}(i)$ in the same manner as the DBR algorithm except that fewer cells are involved in each cluster. If the MT belongs to $G_{\bar{f}}$, BS_i applies the bandwidth reservation policy described in Section 2.2. Figure 3 shows the difference between the DBR scheme and the UPDBR scheme. For UPDBR, each cluster contains only one cell rather than several cells as in the DBR.

When a new connection request is generated in c_i, BS_i first determines the cells involved in P_{UPDBR},[‖] and then it checks available bandwidth using Equation (2). If the condition is satisfied, BS_i establishes $R_I(i)$ and $R_{II}(i)$, and sends reservation request messages to the cells in P_{UPDBR}. The procedure after that is the same as the DBR scheme. When a handoff occurs from a cell c_i to a cell c_j, BS_j checks the available bandwidth for handoff using $N_{\text{used}}(j) + \text{bw} \leq N_{\text{total}}$. In certain situations, an MT may not use the predicted path due to conditions such as traffic congestion or other abnormal events. In such cases, whenever BS_i detects that the MT deviates from the usual path, it transfers the MT from the G_f to the $G_{\bar{f}}$ group.

[‖] P_{UPDBR} denotes the set of cells involved in the predicted path when using the UPDBR algorithm.

2.4. A QoS-Aware Admission Control Scheme

Next we present an admission control policy for new connections. Whenever a new connection request is generated in a current cell c_i, BS_i first checks if Equation (2) can be satisfied. If the condition cannot be satisfied, the new connection is blocked. Otherwise, BS_i constructs $R_I(i)$ and $R_{II}(i)$ based on the current MT's moving direction. For cells which always follow a similar moving pattern, a look-up table of the moving pattern can be saved and used subsequently to reduce the computation overhead [30]. BS_i then sends reservation request messages to the corresponding cells in $R_I(i)$ and $R_{II}(i)$ to check the feasibility of the handoff, given by Equation (2).

$$N_{\text{used}}(i) + \text{bw} \leq N_{\text{total}} - N_{\text{resv}}(i) \tag{2}$$

When a cell, say c_j, in $R_I(i)$ or $R_{II}(i)$ receives a reservation request message from c_i, BS_j executes the algorithm shown in Figure 2, computes its current CDR (ρ_j) and replies to c_i. After BS_i receives reply messages from all the cells in $R_I(i)$ and $R_{II}(i)$, it computes ρ_i, checks average CDR of all cells in $R_I(i)$ and $R_{II}(i)$, denoted as $\rho_{\text{all}}^{\text{avg}}$ and decides whether it can accept the new connection or not.

Let $|c_{i,\text{ack}}|$ and $|c_{i,\text{all}}|$ be the number of cells which sent *ack* messages, and the total number of cells in $R_I(i)$ and $R_{II}(i)$ respectively. Then $|c_{i,\text{all}}|$ is defined as $|c_{i,\text{all}}| = \{c_j \mid c_j \in R_I(i) \vee c_j \in R_{II}(i)\}$ and $c_{i,\text{ack}}$ is defined as $c_{i,\text{ack}} = \{c_j \mid c_j \in c_{i,\text{all}} \wedge c_j \text{ has sent } ack \text{ to } c_i\}$. The average CDR is given by $\rho_i^{\text{avg}} = 1/|c_{i,\text{all}}| + 1\ (\sum_{c_k \in c_{i,\text{all}}} \rho k + \rho_i)$. After receving all the response, the new connection is accepted if Equation (3) is satisfied:

$$|c_{i,\text{all}}| \cdot \psi_i \leq |c_{i,\text{ack}}| \wedge \rho_i^{\text{avg}} \leq T_{\text{QoS}} \tag{3}$$

Here, ψ_i is a system parameter maintained in c_i and can vary dynamically. Once BS_i accepts the new connection, it sends reservation confirm messages to the cells, which sent an ack message for bandwidth reservation or sharing. Otherwise, the new connection is blocked. When BS_i receives a confirm message from c_i, it reserves or shares the bandwidth as specified in Figure 2.

After BS_i makes a decision for a new connection, it changes ψ_i depending on the ρ_i^{avg} value. If the ρ_i^{avg} is higher than T_{QoS}, then it implies that $c_{i,\text{all}}$ currently

```
if (N_used(i) + bw ≤ N_total − N_resv(i)) {
    send reserve message to c_{i,all};     /* call bandwidth reservation algorithm of Figure 2 */
    receive reply from c_{i,all};
    if (| c_{i,all} | · ψ_i ≤ | c_{i,ack} |  ∧  ρ_i^{avg} ≤ T_QoS) {
        accept the new connection;
        N_used(i) = N_used(i) + bw;
    }
    else
        block the new connection;
    if (ρ_i^{avg} > T_QoS)
        ψ_i = min(ψ_i + δ, 1.0);      /* δ = 0.1 in our study */
    else
        ψ_i = max(ψ_i − δ, 0.1);      /* Minimum value of ψ_i = 0.1 */
}
else
    block the new connection;
```

Fig. 4. The admission control scheme used in c_i.

does not have enough reserved or shared bandwidth for the future handoff to keep the ρ_i^{avg} below T_{QoS}. Therefore, accepting a new connection in c_i can degrade ρ_i^{avg}. BS_i can block a new connection by increasing ψ_i by an amount δ. This implies that BS_i has more cells in $c_{i,\text{all}}$ to reserve or share the bandwidth, which in turn lowers the probability of accepting a new connection. However, if the ρ_i^{avg} is less than T_{QoS}, then the system bandwidth in $c_{i,\text{all}}$ is underutilized. In this case, BS_i should accept more new connections by decreasing ψ_i by δ. This helps BS_i in accepting a new connection even though less number of cells in $c_{i,\text{all}}$ reserve or share the bandwidth. The complete admission control algorithm for a new connection is shown in Figure 4.

3. Performance Evaluation

3.1. Simulation Testbed

We use a (6×6) wrap-around cellular network with 1 mile cell diameter to examine the proposed scheme along with two prior schemes [3,21]. We consider two different types of communication sessions: voice and video. The performance evaluation is conducted using the following assumptions: the average connection time (T) is exponentially distributed with a mean of 180 s and the connection arrival follows Poisson distribution with a rate of λ. Speed of an MT is uniformly distributed between 45 and 70 miles per h. The total bandwidth (N_{total}) allocated to each cell is 600 kb/s. The bandwidth for audio (B_{audio}) and video (B_{video}) is 10 Kb/s and 100 kb/s respectively. The percentage distribution of the voice and video connections is given by $P_{\text{voice}} = 0.8$ and $P_{\text{video}} = 1 - P_{\text{voice}} = 0.2$. Similar assumptions have been used in most prior studies [3,8].

We have written an event-driven simulator using CSIM [1] to conduct the performance study. The simulation results are illustrated as a function of the offered load** per cell, where offered load is defined as

$$\text{Offered load} = T \times \lambda \times (P_{\text{voice}} \times B_{\text{voice}} + (1 - P_{\text{voice}}) \times B_{\text{video}}) \qquad (4)$$

Note that for a given offered load, we can find the arrival rate λ since all other parameters in Equation (4) are known. For most of the experiments, we use two clusters and the number of cells in the inner and outer cluster is 3 and 3 respectively. Since the probabilities of moving straight (P_{S}) and moving left or

**The offered load is the total bandwidth required to support all the existing connections in a cell as used in References [7,8,26,31]. For example, if the offered load is 100, the system capacity of a cell is fully used to support the connections. Thus, a cell is over-loaded when the offered load is more than 100. We consider a range of offered load from 20 to 300. Since a high connection requests rate could be generated due to special circumstances, we consider a offered load up to 300 to evaluate our scheme.

Table I. Simulation parameters.

Parameter	Value
Total bandwidth per cell (N_{total})	600 kb/s
Bandwidth for audio (B_{voice})	10 kb/s
Bandwidth for video (B_{video})	100 kb/s
Average connection time (T)	180 s
Sharing rate (ϵ or η)	1.0–3.0
Target QoS for handoff (T_{QoS})	0.01 or 0.02

QoS, Quality of Service.

right (P_L, or P_R) are much higher than the other probabilities, we choose $P_S = 0.5$, $P_L = 0.15$, $P_R = 0.15$, $P_{LL} = 0.075$, $P_{LR} = 0.075$ and $P_S = 0.05$. To simulate the user profile-based DBR scheme, we assume that 70% of the traffic in a cell follows the path defined in the user profiles, while the rest (30%) is assumed to be communication sessions with unknown user profiles. Moreover, it is assumed that an MT follows P_{UPDBR} 80% of the time ($\Phi = 0.8$). In the admission control algorithm, ψ is incremented or decremented by $\delta(=0.1)$ in our experiment. The simulation parameters are summarized in Table I.

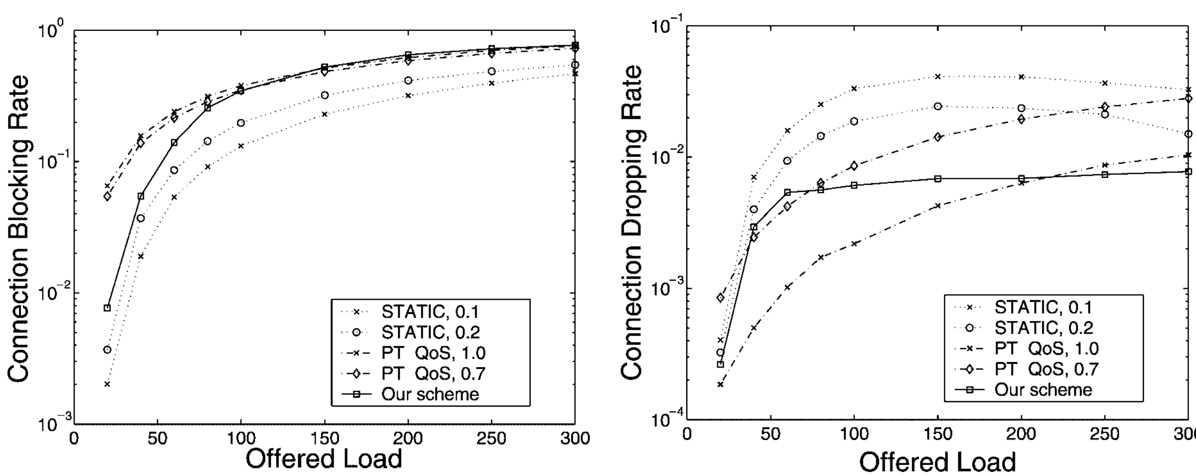
3.2. Simulation Results

The performance parameters measured in this study are CBR, CDR, bandwidth utilization and the number of communication messages. The results are collected using 90% confidence interval and the predicted values lie within ±10% of the mean. First, we conduct a comparative evaluation of our proposed scheme with respect to two prior schemes and then present in-depth evaluation of our approach.

3.2.1. Performance comparison

We start the performance study with a comparative analysis of our approach with the STATIC scheme [21] and the PT-QoS scheme [3]. In case of the static reservation (*STATIC*), a fraction (g) of the total bandwidth in a cell is exclusively reserved for handoffs. This scheme relies only on the local information to admit a new connection, and the current cell does not negotiate with neighboring cells. We experiment with two different values of g ($g = 0.1$ and $g = 0.2$). The PT-QoS approach [3] defines an MLC based on the mobility pattern of the MTs, and reserves bandwidths from a fraction of cells (s) in the MLC based on parameters such as the MT's expected arrival time, latest arrival times and departure time. Unlike our scheme, the PT-QoS algorithm uses a fixed fraction of cells out of all cells in MLC for admission control to admit a new connection and drops the on-going connection if the MT does not conform the prediction. We also use two different values of s ($s = 1.0$ and $s = 0.7$) for performance evaluation. Both these schemes have no mechanism to support QoS guarantee for handoffs. For the differential bandwidth reservation algorithm, we use one cluster in R_I and one cluster in R_{II}, and the two sharing rates. ϵ and η are set to 1.5 and 3.0 respectively.

As shown in Figure 5(a), the STATIC approach has the lowest CBR because it only examines the status of



(a) Connection blocking rate

(b) Connection dropping rate

Fig. 5. Comparisons of the Connection blocking rate (CBR) and Connection dropping rate (CDR) of the proposed scheme ($\epsilon = 1.5$ and $\eta = 3.0$) with the STATIC scheme ($g = 0.1$, 0.2) and the PT-QoS scheme ($S = 1.0$, 0.7).

the current cell, where the new connection request is initiated. As expected, the static scheme with 20% bandwidth reservation performs better than that with 10% reservation. The PT-QoS scheme has the maximum CBR since it reserves more than the required bandwidth for a longer time, and the results for $s = 1.0$ and $s = 0.7$ are almost the same. The proposed scheme has slightly lower CBR than the PT-QoS approach.

Figure 5(b) compares the CDRs of the three schemes. As can be seen, the proposed policy keeps the CDR below the $T_{\mathrm{QoS}}(=0.01)$ compared to the other two schemes. An acceptable CDR of 0.01 or 0.02 has been used as a target QoS in prior studies [7,26]. The PT-QoS approach has a lower CDR than the STATIC scheme except for $g = 0.2$, which shows a little lower CDR than the PT-QoS approach (for $s = 0.7$) when the offered load is high. The PT-QoS approach with $s = 0.7$ has a higher CDR than that with $s = 1.0$ because the former accepts more connections.

Based on the results of Figure 5, we can conclude that the proposed scheme not only provides relatively better performance, but also maintains a stable CDR as specified by T_{QoS} over the entire workload. It has comparable CBR with respect to the STATIC policy. However, the CDR for both STATIC and PT-QoS policies increases with the workload and is higher than the target value of 0.01.

3.2.2. Effect of target QoS

Next, we investigate performance sensitivity of our policy in terms of CBR, CDR and bandwidth utilization for different QoS settings. Figure 6 depicts variations of the CBR and CDR for two target QoS parameters. The results indicate that our integrated scheme keeps the CDR below the target QoS over the entire workload. The CBR, as expected, is slightly higher in Figure 6(a) because a BS blocks more new connections to keep the CDR at 0.01.

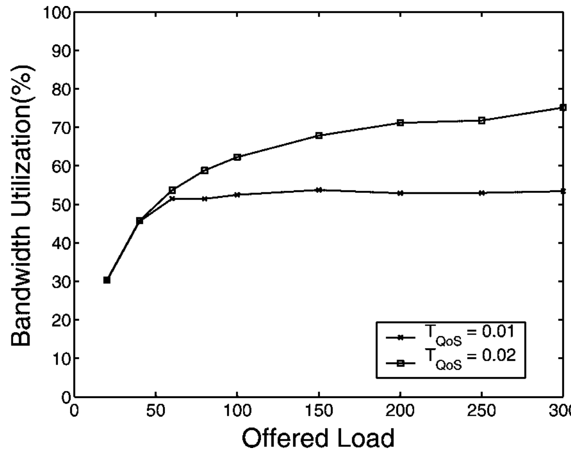
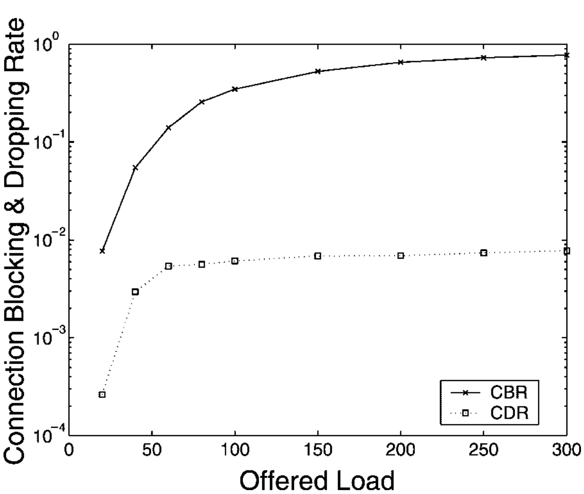


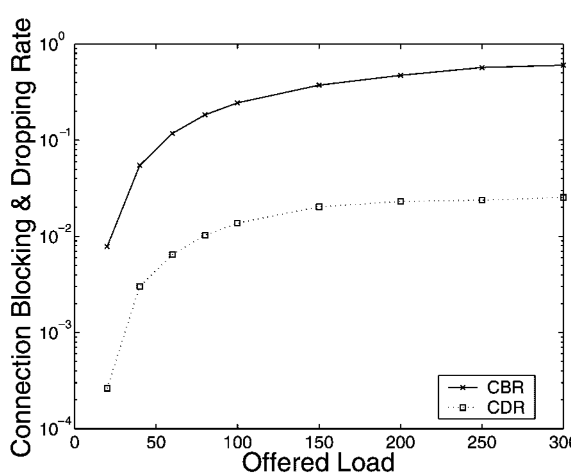
Fig. 7. Bandwidth utilization with different T_{QoS} (0.01 and 0.02).

There is a tradeoff between CDR and bandwidth utilization. Intuitively, if we choose a smaller T_{QoS} value, then more bandwidth will be reserved or shared, CDR will drop, CBR will increase and the bandwidth utilization will be low. In Figure 7, the bandwidth utilization with a smaller T_{QoS} is lower than that with a larger $T_{\mathrm{QoS}}\,(=0.02)$ and the gap between the two gradually increases with the workload.

In Figure 8, we show a snapshot of ψ with time. Note that ψ controls the number of cells that are



(a) $T_{QoS} = 0.01$



(a) $T_{QoS} = 0.02$

Fig. 6. Connection blocking and dropping rate with different T_{QoS} ($\epsilon = 1.5$ and $\eta = 3.0$).

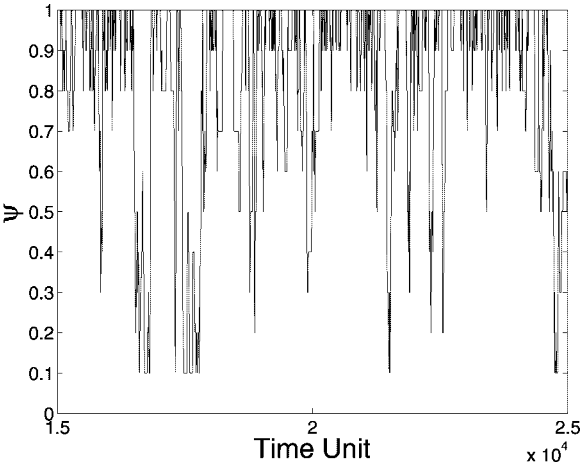


Fig. 8. Snapshot of ψ when the offered load and T_{QoS} are 200 and 0.01 respectively.

involved in admission control by incrementing or decrementing its value to keep the CDR below T_{QoS}. The results indicate that at least 60% of the cells participate in the admission decision most of the time.

Since ψ depends on the current average CDR, not all of the cells need to participate in admission control. In Figure 9, we plot the average number of cells used in admission control for different workloads. The number of participating cells is higher for a tighter QoS parameter ($\mathrm{CDR} = 0.01$). Also, as the workload increases, we observe a slight decrease in the average number of cells participating in the admission decision because less number of cells are available for bandwidth reservation or sharing. A scheme like PT-QoS uses a fixed number of cells (6 in this case $(3+3)$) irrespective of the target QoS constraint.

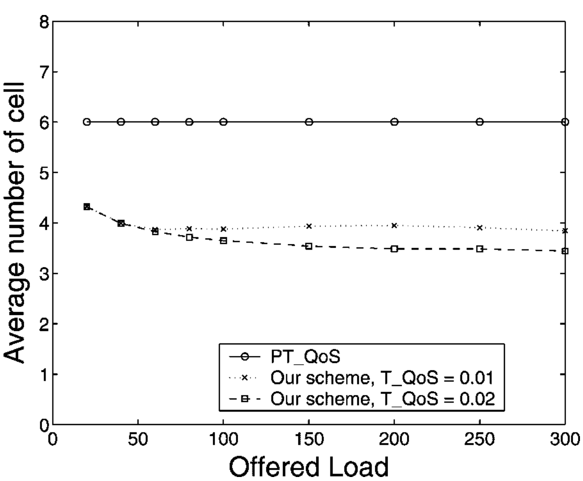


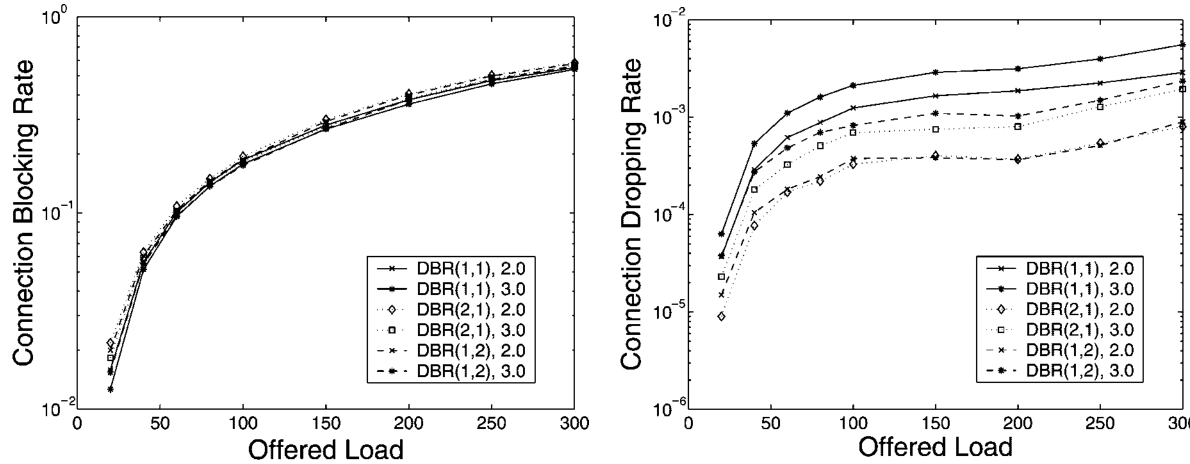
Fig. 9. Comparisons of the average number of cell involved in admission control.

3.2.3. Effect of the sector configurations and system parameters

Next, we examine the impact of sector configurations and other tunable parameters on the performance of the proposed scheme. Three different sector configurations are used: DBR(1,1), DBR(1,2) and DBR(2, 1), where the notation DBR(x, y) represents x clusters in R_I and y clusters in R_{II}. ϵ is varied from 1.0 to 1.5, while η is varied from 1.0 to 3.0. Note that the DBR approach with $\epsilon = \eta = 1.0$ does not allow any bandwidth sharing, and hence, a connection has a high probability of begin blocked and the dropping rate is almost 0 regardless of the sector configurations. Here, we report results for $\epsilon = 1.5$ and $\eta = 2.0$ or 3.0 respectively. For additional results, please refer to Reference [17]. We use a simple admission control of Equation (2) for comparison.

Figure 10 shows the effect of the sector configurations and system parameters on the CBR and CDR. Figure 10(a) depicts that the three DBR configurations have almost similar CBR, although the DBR(1,1) configuration has slightly lower CBR than the other two configurations because it examines a relatively small number of cells during a connection admission control, and thus, the probability of accepting a connection is higher than other sector configurations. In Figure 10(b), the CDR increases as the sharing rate (η) increases since it accepts more connections. Because of examining more cells to admit a connection, DBR(2,1) and DBR(1,2) have less probability of dropping a connection than DBR(1,1). With the same sharing rate (η), the CDR increases in the order of DBR(2,1), DBR(1,2) and DBR(1,1). Also, the results indicate that as η increases, CDR increases.

Figure 11 plots the bandwidth utilization for different sector configurations and indicates that bandwidth utilization increases as the sharing rate increases. Any sector configuration with $\eta = 2.0$ has lower bandwidth utilization because it shares little bandwidth, and hence, most of the bandwidth is used for handoff reservation. As a result, less bandwidth can be used to accept new connection requests, and a connection may be rejected even though some bandwidth is available. The configurations of DBR(2,1) and DBR(1,2) have relatively lower bandwidth utilizations compared to the DBR(1,1) configuration because DBR(2,1) and DBR(1,2) require more cells to make bandwidth reservations.



(a) Connection blocking rate

(b) Connection dropping rate

Fig. 10. CBR and CDR of DBR approach with different sector configurations and sharing rates ($\epsilon = 1.5$ and $\eta = 2.0$ or 3.0).

To examine the effects of the sector angle θ and hence the different number of cells in each cluster of the sector configuration, we use three sector angles (θ_{narrow}, θ_{normal}, θ_{wide}) and two clusters in a sector. This implies one cluster for each of R_I and R_{II}. For θ_{narrow}, the number of cells used in the first and second clusters is 1 and 3 respectively. θ_{normal}, as has been used in the previous experiments, includes 3 and 3 cells in the inner and outer clusters respectively. Finally for θ_{wide}, the number of cells used in the first and second clusters is 3 and 5 respectively.

Figure 12 shows the CBR and CDR with and without a target QoS for the three sector angles. Neither a target QoS nor a QoS-aware admission control mechanism is used in Figure 12(a). The admission decision is made only using the status of the current cell. As θ increases, more cells are involved in each cluster and more bandwidth is reserved or shared. As expected, the CDR increases when the sector angle θ becomes narrow. The CBR exhibits an opposite trend compared to the CDR although the results are much close. Figure 12(b) shows the effect of the admission control mechanism. The CDR for all three sector angle configurations are very similar, stable and are within the specified T_{QoS} value (0.01). This implies that one can use a smaller sector with less number of cells to satisfy the QoS requirement, and thereby, the other cells can be used for handling additional connections.

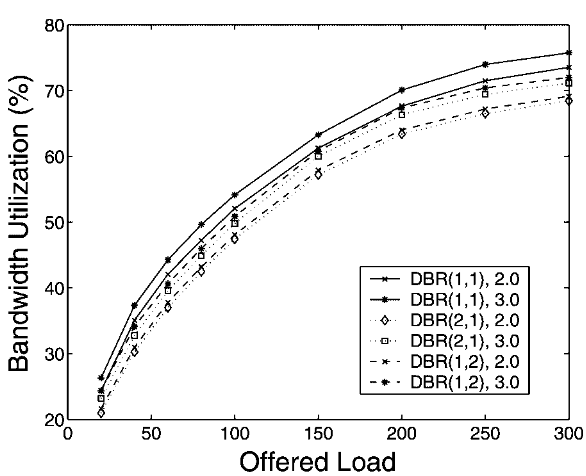
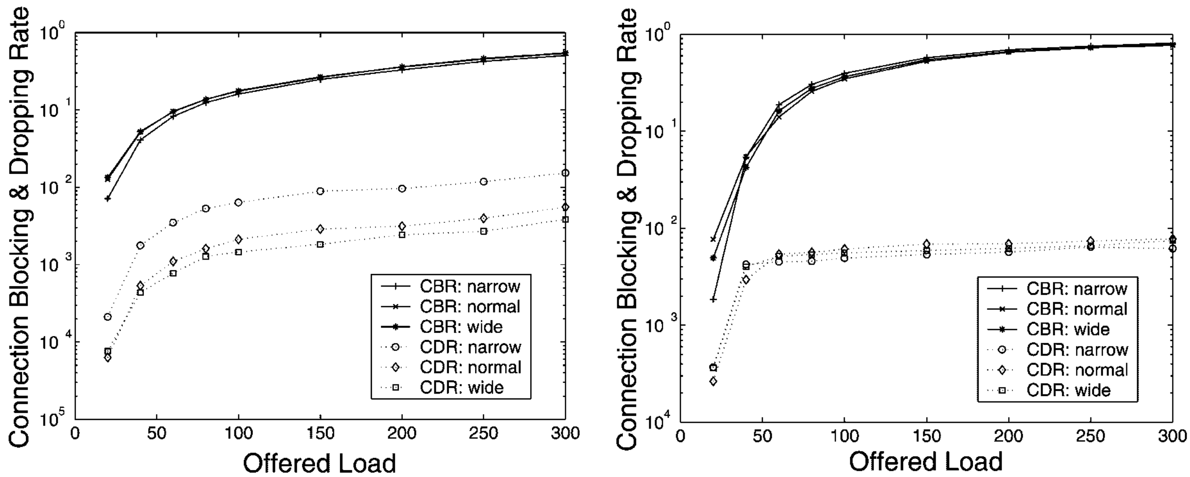


Fig. 11. Bandwidth utilization of DBR approach with different sector configurations and sharing rates ($\epsilon = 1.5$ and $\eta = 2.0$ or 3.0).

3.2.4. *Effect of user mobility*

Finally, we compare the performance of the UPDBR approach and the DBR approach in terms of CBR, CDR, bandwidth utilization and communication message overhead. The number of cells in the first, second and third sectors are confined to 3, 3 and 5 in the study because the probabilities of moving straight (P_S) and moving left or right (P_L or P_R) are much higher than other probabilities. It was observed that adding more cells to the sectors did not provide additional performance improvements. We neither use a target QoS nor a QoS-aware admission control, but a simple admission control algorithm. A simple admission control decision based on Equation (2) is used for DBR and UPDBR.

The UPDBR approach reserves less bandwidth compared to the DBR approach by making use of the user profile. As a result, more new connections can



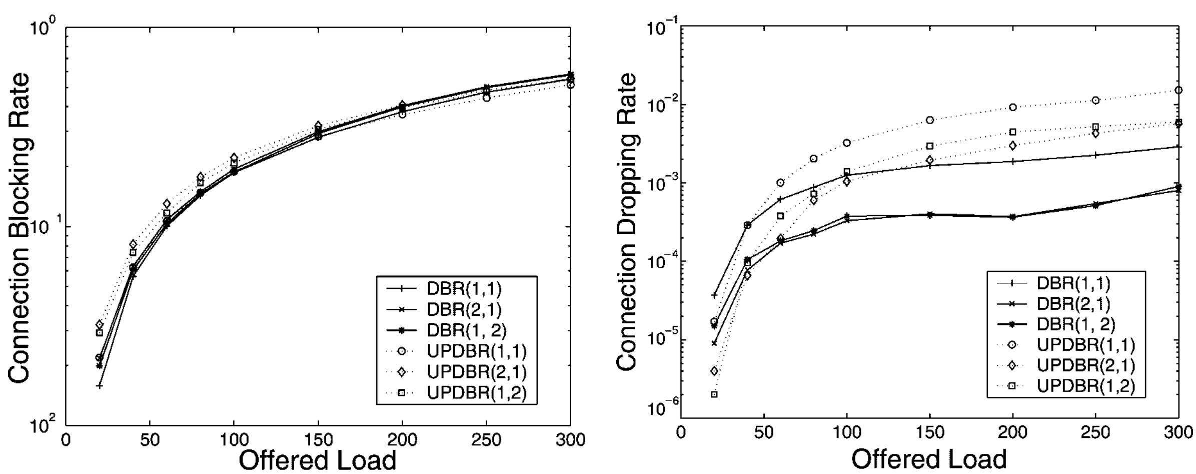
(a) Without T_{QoS} (b) With T_{QoS} (0.01)

Fig. 12. Connection blocking and dropping rate with different number of cells in each cluster.

be accepted. This explains why the UPDBR approach has slightly lower CBR than the DBR approach in Figure 13(a). Since the DBR approach reserves more bandwidth for handoffs, its CDR is lower than the UPDBR approach, as shown in the Figure 13(b). UPDBR(2,1) and UPDBR(1,2) schemes have lower CDR than UPDBR(1,1) because they use more cells to make bandwidth reservations, and thus, a connection has a lower probability to be dropped if the MT follows the path defined in its user profile.

There is a tradeoff between CDR and bandwidth utilization. Intuitively, if we reserve more bandwidth, the CDR will be reduced, but the bandwidth utilization becomes low. In Figure 14(a), the bandwidth utilization of the UPDBR approach is higher than the DBR approach over the entire workload. The DBR approach has low bandwidth utilization since it reserves more bandwidth compared to the UPDBR approach. As explained earlier, when the number of cells to make bandwidth reservation reduces, the amount of bandwidth, which can be used to support new connections, increases. This explains why UPDBR(1,1) has a higher bandwidth utilization than UPDBR(2,1) and UPDBR(1,2).

As shown in Figure 14(b), the UPDBR approach has much less message overhead compared to the DBR approach. Compared to the DBR approach, it reduces the communication messages by almost half



(a) Connection blocking rate (b) Connection dropping rate

Fig. 13. Comparisons of the UPDBR approach to the DBR approach ($\epsilon = 1.5$ and $\eta = 2.0$).

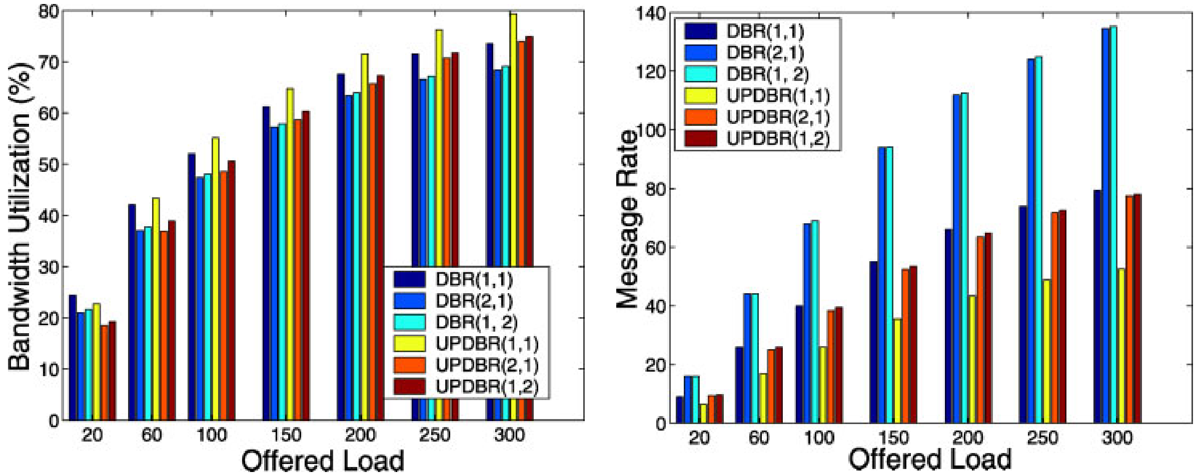


Fig. 14. Comparisons of the UPDBR approach to the DBR approach ($\epsilon = 1.5$ and $\eta = 2.0$). Six bars for different policies and sector configurations are shown against offered load. The DBR(1,1), DBR(2,1), DBR(1,2), UPDBR(1,1), UPDBR(2,1) and UPDBR(1,2) schemes are plotted from left to right.

when the offered load reaches 300%. In both the UPDBR and DBR schemes, cells need to communicate with each other to make bandwidth reservations. However, in the UPDBR approach, the current cell (where the MT connection request was originated) only sends reservation messages to the cells through which the MT will move, instead of all possible paths used in the DBR. As long as the MT follows the predicted paths, the number of communication messages of UPDBR will be much smaller than that of the DBR approach.

4. Concluding Remarks

In this paper, we have proposed a unified DBR algorithm and a QoS-aware admission control scheme for cellular networks to guarantee a required level of QoS to on-going connections, while maintaining a competitive CBR for new connections. With the DBR scheme, the possible path of an MT that spans over a set of cells is divided into a couple of clusters in the form of a sector. The cells in the sector are further divided into two regions depending on whether they have an immediate impact on the handoff or not. Two different reservation policies are applied for these two regions. In addition, a variation of the DBR algorithm, called UPDBR, exploits the moving pattern of an user to make efficient bandwidth reservation by minimizing the number of participating cells in handoff. Our admission control scheme, like prior studies, assumes *a priori* knowledge of the possible path of a new connection. This information is used to check the availability of the required bandwidth in a sector of cells prior to making the admission decision. However, unlike the prior schemes, the admission control algorithm uses a subset of cells in the sector to check if the required CDR can be maintained. The number of cells required for bandwidth reservation varies dynamically based on the average CDR of the cells in the sector.

Extensive simulations were conducted to compare the performance of the proposed schemes with the prior STATIC and PT-QoS policies. Unlike the prior policies, our approach can guarantee the required CDR over the entire workload, while maintaining a competitive CBR. The improved and guaranteed performance is possible by dynamically selecting the number of cells required to satisfy the QoS assurance. Also, the admission control policy is quite adaptable to different QoS requirements.

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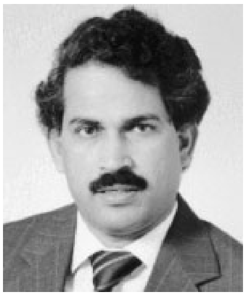

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