FIRST QUARTER 2005, VOLUME 7, NO. 1

IEEE COMMUNICATIONS SURVEYS

The Electronic Magazine of Original Peer-Reviewed Survey Articles

www.comsoc.org/pubs/surveys

CALL ADMISSION CONTROL IN WIRELESS NETWORKS: A COMPREHENSIVE SURVEY

MOHAMED HOSSAM AHMED, MEMORIAL UNIVERSITY OF NEWFOUNDLAND

ABSTRACT

Radio resource management (RRM) plays a major role in Quality of Service (QoS) provisioning for wireless communication systems. The performance of RRM techniques has a direct impact on each user's individual performance and on the overall network performance. Arriving (new and handoff) calls are granted/denied access to the network by the call admission scheme (CAC) based on predefined criteria, taking the network loading conditions into consideration. CAC in wireless networks has been receiving a great deal of attention during the last two decades due to the growing popularity of wireless communications and the central role that CAC plays in QoS provisioning in terms of the signal quality, call blocking and dropping probabilities, packet delay and loss rate, and transmission rate. In the first and second generation of wireless systems, CAC has been developed for a single service environment. In the third generation and beyond wireless systems, multimedia services such as voice, video, data, and audio are to be offered with various QoS profiles. Hence, more sophisticated CAC schemes are developed to cope with these changes. This article provides a comprehensive survey of CAC schemes in modern wireless networks.

Radio resource management (RRM) plays a major role in Quality of Service (QoS) provisioning for wireless communication systems. As a matter of fact, RRM policies, along with the network planning and air interface design, determine QoS performance at the individual user level and the network level as well. RRM techniques encompass frequency and/or time channels, transmit power, and access to base stations [1] in order to control the amount of the assigned resources to each user with the objective of maximizing some function such as the total network throughput, total resource utilization, or total network revenue, subject to some constraints such as the maximum call blocking/dropping rate and/or the minimum signal to interference ratio. The performance of RRM techniques has a direct impact on each user's individual performance and, more importantly, on the overall network performance. For instance, the allocated transmitter power for a user not only determines the QoS offered to this user, it also affects the interference level that other users receive, and as a result it influences the signal quality of other users.

Radio resources are managed using various schemes that can be grouped in three sets. The first set includes frequency/time resource allocation schemes such as channel allocation, scheduling, transmission rate control, and bandwidth reservation schemes. The second set consists of power allocation and control schemes, which control the transmitter power of the terminals and the base stations. The third set comprises call admission control, base station (BS) assignment, and handoff algorithms, which control the access port connection.

As shown in Fig. 1, arriving calls are granted/denied access to the network by the call admission scheme (CAC) based on predefined criteria, taking the network loading conditions into consideration. Traffic of admitted calls is then controlled by other RRM techniques such as scheduling, handoff, power, and rate control schemes.

CAC has been extensively studied in wireline networks as an essential tool for congestion control and QoS provisioning. Different aspects of CAC design and performance analysis, particularly in the context of broadband integrated service digital network (B-ISDN) based on asynchronous transfer mode (ATM) technology, have been investigated in [2]. However, the problem of CAC in wireless networks is more sophisticated due to the unique features of wireless networks such as channel multiple access interference, channel impairments, handoff requirements, and limited bandwidth.

CAC in wireless networks has been receiving a great deal of attention during the last two decades due to the growing popularity of wireless communications and the central role that CAC plays in QoS provisioning in terms of the signal quality, call blocking and dropping probabilities, packet delay and loss rate, and transmission rate. In the first and second generation of wireless systems, CAC has been developed for a single service environment. In third generation (3G) wireless systems, multimedia services such as voice, video, data, and audio are offered with various QoS profiles. Hence, more sophisticated CAC schemes are developed to cope with these changes.

This article provides an overview of various aspects of CAC schemes in modern wireless networks. The next section discusses the main reasons of using CAC schemes. Then, a classification of CAC schemes is provided. Next, CAC for controlling signal quality is discussed. The following section analyzes CAC schemes for controlling call dropping probability. CAC schemes for controlling packet-level QoS parameters and for transmission rate control are discussed in the following two sections. Then, revenue-based CAC schemes are discussed followed by CAC for service/class prioritization. Then, CAC for fairness is presented. Finally, the emerging trends and future research issues are discussed in the last section.

Main Reasons for Using CAC Schemes

To guarantee QoS parameters

Signal Quality: CAC is essential to guarantee the signal quality in interference-limited wireless networks. For instance, CDMA wireless networks have a soft capacity limit so that the more loaded the network is, the more deteriorated is the signal quality for users in terms of the interference level or the signal to interference ratio (SIR). Hence, CAC schemes admit users only if it can maintain a minimum signal quality to admitted users (including the new call and existing calls). In this case, the admission criterion can be the number of users (per cell and/or per group of neighbor cells), interference level or SIR, total transmitted power by BS, or received power by either BS or the mobile station.

Call Dropping Probability: Since dropping an active call is usually more annoying than blocking a new call, CAC is employed in bandwidth-limited wireless networks to control the handoff failure probability (P_{hf}). This can be implemented by reserving some resources for handoff calls exclusively. The admission criterion can be either the number of users (per class in a multiple-class system) or an estimate of handoff failure probability. Resources availability can also be used as a criterion for admission. Whatever the used admission criterion, handoff calls receive less stringent admission conditions compared with a new call, which might lead to an increase in the new call blocking rate (P_b).

Packet-Level Parameters: When packet-oriented services are provided by wireless networks, network overloading can cause unacceptable excessive packet delay and/or delay jitter. The throughput level at the network or user level can also be dropped to unbearable levels. Therefore, CAC should be used to limit the network level to guarantee packet-level QoS parameters (packet delay, delay jitter, and throughput). In this case, the number of users, resource availability and/or an estimate of the packet-level QoS parameters can be utilized as an admission criterion.

Transmission Rate: CAC schemes are used in wireless networks offering data services to guarantee a minimum transmission rate. The use of CAC to ensure a minimum transmission rate has been studied extensively in wireline networks. The problem, however, is more complicated in wireless networks because of user mobility (implying handoff and link quality variations), limited bandwidth, and mutual cochannel interference.

Others

Revenue-Based CAC: From the network perspective, a new call admission has both rewards and penalties. The reward comes from the utilization of network resources for a certain amount of revenue. However, there is a potential penalty, particularly at high network loading values, which can be manifested as deterioration in the QoS offered to the already admitted users and even potentially some call dropping. Hence, CAC can be used to increase the network revenue function based on the potential reward and penalty of admitting new calls. In this case, the admission criterion can be the number of users or an estimate of the probability of QoS deterioration (e.g. lower transmission rate than the acceptable level).

Prioritize Some Services/Classes: Giving higher priority to

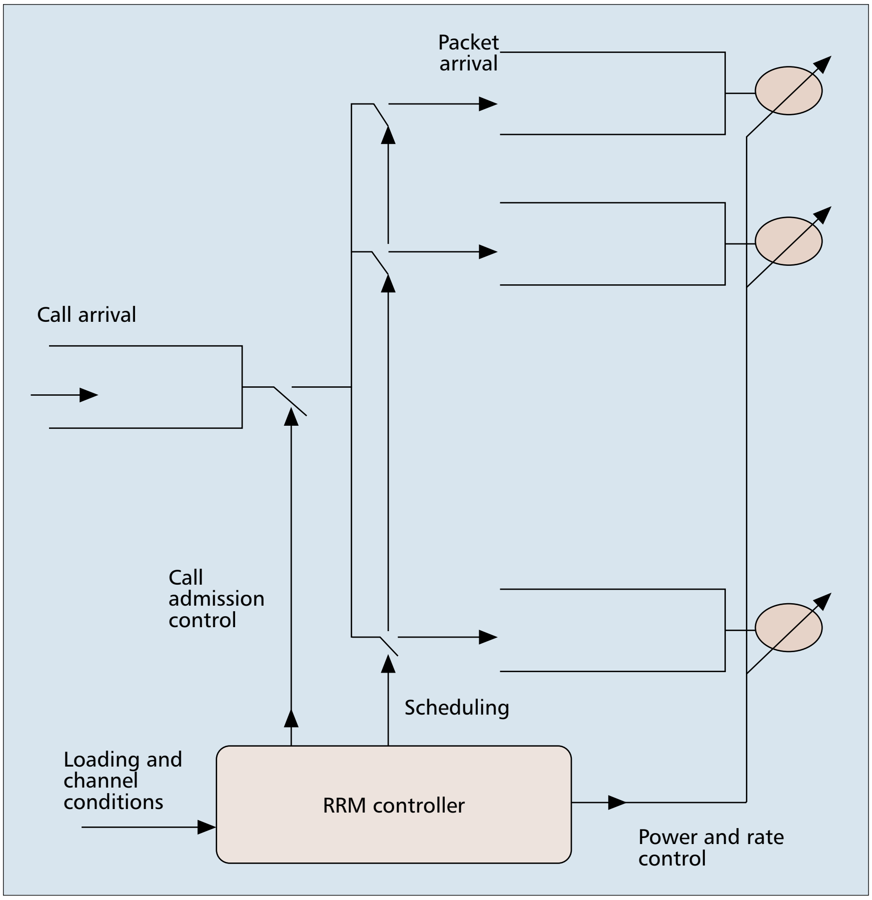


Figure 1. *Radio resource management model.*

some services or classes can be one of the objectives of CAC schemes. For instance, there is a common belief among network operators and researchers as well that voice services should be given higher priority over data services since the former are more rewarding (at least for the time being) to the network operators. Also, giving higher priority to some classes inside the same service might be needed to differentiate between different user classes based on some criteria such as the subscription fees or the urgency of the call.

Fair Resource Sharing: Fairness among different users in the same class (with different channel conditions and mobility characteristics) and among users of different classes is one of the objectives of CAC. CAC can be employed to admit/reject users based on the allocated resources such that no user class dominates the system resources.

CAC Classification

CAC schemes can be classified based on various design options. Each design option has its own advantages and disadvantages, as discussed below. Table 1 lists the different design options with their advantages, disadvantages, and some comments. For instance, CAC schemes are classified based on the centralization of the decision making as centralized and distributed. In centralized schemes one entity such as the mobile switching center (MSC) controls the admission in the whole network (e.g., [3, 4]), while in distributed schemes CAC is performed in each cell by the BS (e.g., [5, 6]). Central CAC schemes can be more efficient (due to the global information availability) but they are more complex, and that is why they are not used in real wireless networks.

The amount of available information for the admission controller might span the whole network, as in global CAC schemes (e.g., [3, 4]); consider a restricted area in the network (a cluster or all surrounding cells of the incoming call), as in semi-local schemes (e.g., [6, 7]); or limit itself to the information in the cell of the incoming call, as in local schemes (e.g., [5, 8]). Global information can be implemented in a distributed manner if information exchange between BSs is employed.

CAC schemes can be classified based upon the number of services/classes. Single-class CAC has been dominant in first and second generation (2G) wireless networks when voice service was the main (and sometime the only) offered service (e.g., [5, 9]). With the growing interest of data and multimedia services, single-class CAC schemes are no longer sufficient, and as a result multiple-service/class CAC schemes are more relevant (e.g., [7, 10]), specially in the enhanced second generation (2.5G) and third generations and beyond (3G/4G). The design of multiple-service/class CAC schemes is more challenging since some critical issues, such as service prioritization, fairness, and resource sharing policy, must be considered.

Optimal CAC schemes (e.g., [11–13]) are always preferred, but they are not necessarily attainable, particularly in realistic scenarios with a large problem size and complicated system parameter interdependence. As such, heuristics and intelligent techniques (e.g., [3, 14]) are widely used to find suboptimal CAC scheme.

CAC schemes can be classified as proactive (parameter-based) or reactive (measurement-based). In proactive CAC schemes (e.g., [10, 15]), the incoming call is admitted/denied based on some predictive/analytical assessment of the QoS constraints. In reactive CAC schemes (e.g., [5, 16]), the incoming call might start transmission (by transmitting some probing packets or using reduced power). Then the reactive CAC scheme decides to admit/reject the call based on the QoS measurements during the transmission attempt at the beginning.

CAC can also be classified based on the information needed in the CAC process [17]. Some CAC schemes use the cell occupancy information [12, 18]. This class of CAC schemes requires a model or some assumption for the cell occupancy. Alternatively, CAC schemes might use mobility information (or estimation) in making the admission decision. The use of mobility information, however, is more complicated and requires more signaling.

The information granularity used in CAC schemes can be considered at the cell level or at the user level. If a uniform traffic model is assumed, information of one cell is enough to represent the whole network condition. In a non-uniform traffic model, however, information from different cells is required to model the network status, which increases the information size. The third case, in which information of each individual user is considered, of course leads to a huge information size.

CAC schemes have been designed either for the uplink (as in [9, 15]) or the downlink (as in [19, 20]). In the uplink, transmit power constraint is more serious than in the downlink since the MS is battery operated. On the other hand, CAC in the downlink needs information feedback from MSs to the BSs for efficient resource utilization. Applying CAC for both links jointly is crucial since some calls might be admissible in one of the links and non-admissible in the other, particularly for asymmetrical traffic. Jeon and Jeong have proposed in [21] a joint CAC scheme for both the uplink and downlink. The call request is admitted only if it is admissible in both uplink and downlink. The asymmetry between uplink and downlink traffic, which is one of the characteristics of some multimedia services such as Web browsing, has been taken into account by adjusting the allocated bandwidth to each link in the CAC based on the traffic characteristics in each link. It has been shown in [21] that this asymmetric allocation enhances resource utilization and other QoS parameters such as P_b and P_{hf}. This work has been extended in [21] to investigate the same problem in CDMA networks. The impact of the bandwidth allocation between UL and DL on QoS parameters (P_b, P_{hf} and outage probability (P_{out})) has been analyzed using a SIR-based CAC scheme for voice and data (asymmetric) services. It has been shown that there is an optimum bandwidth allocation that minimizes the P_b, P_{hf} and P_{out}.

CAC for Controlling the Signal Quality

The signal to interference and noise ratio (SINR) is usually used as a good metric of the signal quality since there is always a direct mapping between the SINR and the bit error rate (BER) given particular coding and modulation techniques. Therefore, the outage probability (P_{out}) is usually defined as the probability that $SINR < SINR_{min}$ where $SINR_{min}$ is the minimum acceptable SINR. In interference-limited networks, the noise part is usually neglected and the signal to interference ratio (SIR) is usually used instead of SINR. Most CAC schemes that control the signal quality attempt to achieve a minimum SIR (SIR_{min}) or equivalently the energy per bit to interference density ratio (E_b/I_o). CAC for controlling the signal quality can be implemented in different approaches, as shown in Table 2.

In the following subsections, the CAC approaches listed in Table 2 are discussed in some detail based on the published work in the literature. These CAC schemes are mainly developed for CDMA networks. CAC schemes for controlling the signal quality in TDMA systems are discussed later. These CAC schemes are either interference/SIR-based or loading-based.

Design choice	Option	Advantages	Disadvantages	Comments
Centralization	Central	More efficient	Complex, unreliable	Unrealistic
	Distributed	Simple More reliable	Less efficient	Commonly used
Information scale	Global	Most efficient	Most complex	Needs information exchange for distributed realization
	Semi-local	Efficient Less complex	Moderate complexity	Needs less information exchange
	Local	Simplest	Least efficient	No need for information exchange
Service dimension	Single service/class	—	—	Suits 1G/2G networks
	Multiple service/class	—	—	Needed in 2.5G, 3G/4G networks
Optimization	Optimal	More efficient	Harder to find Based on simplified assumptions	More desirable (particularly the revenue-based schemes)
	Suboptimal	More realistic Scalable	Less efficient	Heuristic and intelligent techniques
Decision time	Proactive	Fast	More error-prone Needs prior information	Also called parameter-based
	Reactive	Less error-prone No need for prior information	Slow	Also called measurement-based
Information type	Cell occupancy	No need for mobility estimation	Needs a cell occupancy model	—
	Mobility	No need for a cell-occupancy model	Needs mobility estimation	—
Information granularity	Uniform cell-based	Simplicity	Coarse granularity	—
	Non-uniform cell-based	Suitable for non-uniform traffic	Medium information size	—
	User-based	Most accurate information	Large information size	—
Considered link	Uplink	—	—	Transmit power is very limited
	Downlink	—	—	Information feedback from MSs to BSs might be needed

Table 1. *Different design choices of CAC schemes.*

Interference and SIR-based CAC

The most straightforward method to achieve a minimum SIR value (SIR_{min}) for controlling the signal quality is to check the SIR value that can be achieved by the new call and admit the call if and only if this value is higher than the minimum SIR value. Various SIR-based CAC schemes have been proposed in the literature. In [9] two SIR-based CAC schemes have been proposed. Both schemes use the residual capacity (R_k) defined below as the admission criterion:

$$R_k = \left\lfloor \frac{1}{SIR_{th}} - \frac{1}{SIR_k} \right\rfloor \quad (1)$$

where SIR_k is the uplink SIR in cell k, SIR_{th} is the threshold SIR, which is a design parameter ($SIR_{th} > SIR_{min}$), and $\lfloor x \rfloor$ is the largest integer smaller than x. The residual capacity (R_k) is calculated periodically, and when a new user arrives at cell k, BS k checks whether R_k is greater than zero to admit the new call, otherwise the new call is rejected. The second algorithm modifies the definition of the residual capacity to take into consideration the impact of admitting the new call on cell k itself and its adjacent cells as well. Thereupon, the admission criterion is chosen to be the minimum residual capacity of the target cells and its adjacent cells as well where the residual capacity in the adjacent cells is modified as follows

$$R_{k,j} = \left\lfloor \frac{1}{\beta}\left(\frac{1}{SIR_{th}} - \frac{1}{SIR_j} \right) \right\rfloor j \in C(k) \quad (2)$$

where β represents the interference coupling between adjacent cells and $C(k)$ is the set of adjacent cells to cell k. If the minimum residual capacity is positive, BS k admits the new user, otherwise it is rejected. Results show that the first algorithm outperforms the second algorithm with homogenous traffic, while with hot spot traffic the second algorithm is superior to the first algorithm. In addition, results showed that both algorithms slightly outperform fixed CAC (with a fixed maximum number of users) in terms of P_b and P_{out}. The definition of residual capacity has been modified in [28] to be able to predict more accurately the impact of admitting a new call in the target cell on its neighbor cells including adjacent and nonadjacent cells. Therefore, the residual capacity is given as

$$R_{k,j} = \left\lfloor \frac{1}{SIR_{th}} - \frac{1}{SIR_j} - \frac{1}{L_m(j,k)} \right\rfloor j \in C(k) \quad (3)$$

Approach	Brief explanation	Seminal work	Comments
Interference & SIR-based CAC	The incoming call is admitted if the interference level (SIR) is less (greater) than a predefined threshold value.	[9, 15, 22]	Needs measurements
Loading	The admission is based on the number of users or resource utilization factor.	[22, 23]	Simple to implement
Effective bandwidth	The maximum number of admissible users is determined using the effective bandwidth concept.	[24]	Efficient, but based on approximations.
Power allocation feasibility	The incoming call is admitted if a feasible power allocation is determined.	[25]	Based on PC model or measurements
Transmitted/received power	The total transmitted/received power is used as the admission criterion.	[26]	Total Tx/Rx power is an indictor of the interference level
Optimum CAC with signal quality constraint	An admission policy is determined by optimizing some objective function subject to signal quality constraint.	[27]	Usually solved by Markovian Decision Process

Table 2. *Various approaches of CAC for controlling signal quality.*

where $L_m(j,k)$ represents the predicted additional inter-cell interference to BS j if mobile user m is admitted into cell k. Significant enhancement in P_{out} and slight reduction in P_b have been achieved by including these modifications proposed by [28]. An upper bound of SIR_{th} has been given in [29] to maintain a specified level for blocking rate.

The estimates of the lowest SIR level in the home cell and adjacent cells, in addition to the estimates of the short term and long-term P_{out}, are employed in [30] for call admission in WCDMA. It is assumed that multiuser detection is employed, which is taken into consideration in the SIR estimation. A fuzzy logic-based scheme decides to admit the incoming call based on the estimated values of SIR and P_{out}. Results show that the proposed scheme outperforms conventional SIR-based CAC in terms of system capacity and outage probability.

An integrated SIR-based resource management scheme that encompasses CAC, handoff, power control (PC), and dynamic channel allocation (DCA) has been proposed in [31]. The CAC scheme simply compares the achievable SIR of the new user with a threshold value $\mathrm{SIR}_{\mathrm{new}}$ and admits the new user only if $\mathrm{SIR} > \mathrm{SIR}_{\mathrm{new}}$. It can be easily shown that this CAC scheme is equivalent to the first algorithm proposed in [9].

An SIR-based CAC has been proposed in [32] for indoor wireless multimedia systems. In this algorithm, different threshold values of SIR are used for each class of traffic depending on the required BER, taking into account the BER due to packet loss in the overflowed buffers in the fixed network.

The impact of SIR-based schemes on the spatial distribution of blocking probability (P_b) in WCDMA has been analyzed in [33]. It has been shown that in a hexagonal cell structure, P_b increases from 1.5 percent to 3 percent as the distance between the MS and the BS increases from 0.1 to 0.5 km. A further increase in the distance does not lead to any significant change in P_b. However, in a realistic network environment, P_b has larger spatial variation. It has been found that P_b can be as high as 50 percent at the cell border even if it is less than 5 percent in the middle of the cell.

In [34] a SIR-based CAC scheme has been proposed for hybrid T/CDMA (TDMA and CDMA) systems supporting both voice and data services. Two different approaches are used in this work. The first approach uses multicode T/CDMA allocation for data users, while the second approach uses multislot T/CDMA allocation for data users. Voice users are assigned a single code and a single slot in both approaches. In the first approach, the call is admitted if there is at least one time slot with R codes that meets the SIR condition (minimum SIR can be achieved for a new user as well as existing users), where R is the ratio of the transmission rate of data users to that of voice users. On the other hand, in the second approach the SIR condition must be satisfied in all R time slots with only one code per each slot. It is worth noting that it is not necessary to assign the same code in the R time slots. It has been shown that multicode T/CDMA outperforms multislot T/CDMA in terms of system capacity, and also allows a tradeoff between the system capacity and the transmission rate. CAC in multicode CDMA is also investigated in [35]. The proposed scheme orders users based on their required E_b/N_0. Then, users are activated starting from the user with the lowest E_b/N_0, then the user with the second lowest E_b/N_0, and so on. Before admitting a user, the CAC scheme checks whether the user can be assigned a minimum number of codes (corresponding to the minimum transmission rate). If the minimum number of codes can be assigned without violating the constraints on E_b/N_0, the user is admitted. Next, additional codes are attempted to be assigned (one by one) to the user to increase the transmission rate up to the maximum designated rate of this user. Then the system proceeds to the next user (next higher E_b/N_0) until all users are checked such that every user is either admitted and allocated multiple codes or rejected due to system infeasibility.

Instead of using SIR as a criterion for call admission, the CAC scheme proposed in [36] employs the estimated outage probability ($\Pr(SIR < SIR_{min})$) as a criterion for call admission. The outage probability of each class is estimated based on the number of users in each class and the power allocated to each active user. The outage probability is estimated using the assumption of imperfect power control, which renders the SIR distribution log-normally. The new call is admitted only if the outage probability of each class is lower than the corresponding required level.

Interference-based CAC schemes use the interference level as an admission criterion to guarantee the signal quality in terms of SIR.

In [15] a framework for adaptive traffic interference-based admission is presented. In order to accommodate variable-rate services with a non-stationary and non-uniform traffic, a good estimation of the interference level of the incoming calls must be utilized. Two call admission strategies for the uplink in CDMA are proposed. These two admission algorithms mainly differ in the amount of information used for deciding to admit/reject the incoming call. The first algorithm, called local adaptive strategy, uses the traffic parameters and the channel characteristics in the cell. The second technique, called global adaptive strategy, extends the scope of the information sources to include all the neighboring cells. There are two main parts of the proposed framework: the estimation part and the decision part. In the estimation part, the mean and variance of the interference level are estimated using the mean and variance of the interference level of the active calls from the measurements using a Kalman filter. The mean and variance of the interference due to the new call are also predicted. The total interference is assessed as the sum of the estimated interference of the active calls, the predicted interference due to the new call, and the reservation threshold (a reservation for the estimated interference variance and errors). Then the decision part decides whether or not to admit the new call by comparing the total interference to the maximum interference threshold I_{max}.

Results show that the Kalman filter reduces the estimation error, and as a result a better utilization of the system resources can be achieved by using a smaller reservation parameter. The local strategy gives a capacity gain in the order of 10–27 percent compared with the fixed strategy (fixed traffic threshold-based CAC) depending on the traffic spatial distribution, while the global strategy gives a capacity gain in the order of 17–33 percent compared with the fixed strategy.

J. Chang *et al.* proposed in [37] a local interference-based CAC scheme that supports voice and stream-type data services with an interference suppression option for data users to prioritize handoff voice calls, as discussed above.

In [38] two threshold values of the interference level-thresholds are used: the first threshold is for users inside the inner part of the cell (closer to the BS), while the second threshold is used for cells close the cell border. The incentive here is imposing higher blocking on calls that are likely to introduce high interference. However, this approach violates the fairness among users and its capacity gain is very limited.

Loading

Maintaining the signal quality in terms of SIR can be realized by controlling the cell/network loading since the higher the number of users, the lower SIR will be. In [39, 40] loading-based CAC schemes are employed to control the number of users using two threshold values M_v and M_d for voice and data users, respectively. M_v and M_d are design parameters whose relative values determine the prioritization of one of the two services over the other. The effective load defined as a weighted sum of the number of users in the cell with higher weights for users far from the BS (closer to the cell border) has been employed in [41] as an admission criterion.

An interesting comparison between loading-based CAC schemes and interference-based CAC schemes has been introduced in [22]. The performance in terms of P_b and the loss probability of communication quality (P_{loss}) of these two CAC categories has been determined analytically and by simulation. It has been shown that the performance of the two CAC categories is almost the same. However, the interference-based CAC schemes have an advantage, that is, the threshold value has less sensitivity on other system parameters of the propagation model, traffic distribution, or the transmission rate, while the loading-based CAC is preferred because of its simplicity and the ease of implementation without the need for measuring the interference level.

In [23] the cell loading in multi-class traffic is expressed in terms of a new function called bandwidth utility (BU), which is defined as

$$BU = \frac{1}{MN}\sum_k \frac{SIR_k}{1+SIR_k} \tag{4}$$

where M is the number of antenna elements, N is the spreading factor, and SIR_k is the minimum SIR value of class k users. The dependence of the maximum BU on the other cell interference (I_{other}) is determined where the maximum BU is calculated by trying all different combinations of the number of users in each class. Then the maximum value of BU at which the SIR target is still achievable is chosen. Then when a new call arrives to the system, I_{other} is measured and the maximum BU is found. Subsequently, the new call is admitted if the current BU in the network (due to active calls) plus the BU of the new call is less than the maximum BU; otherwise, the call is rejected.

Effective Bandwidth–Based CAC

Limiting the number of users per cell is used as shown above to ensure the SIR requirements. However, the selection of the maximum number of users per cell (N) depends heavily on the interference level (I), which is inherently random. Although finding N using the peak value of I can guarantee the SIR requirements, this can underestimate the system capacity. On the other hand, the use of the mean value of the interference can lead to a higher capacity but at the expense of unacceptable signal quality. Hence, a probabilistic guarantee can be used by expressing the SIR requirement as follows [42, 43]

$$P(I > W/R) < L \tag{5}$$

where W is the system bandwidth, R is the transmission rate, and L is a system parameter that determines the signal quality reliability. This formulation is very similar to the CAC problem of variable sources in ATM networks, which is always solved by allocating a certain amount of bandwidth somewhere between the mean and peak values (effective bandwidth). This effective bandwidth is chosen such that it can guarantee the packet loss requirements to each user [24]. The amount of effective bandwidth is usually found by solving the above inequality using two approaches. The first approach is the Gaussian approximation of the random variable, which is the interference level (I) in this case, while the second method uses the Chernoff bound to approximate the above inequality [24, 44].

Power Allocation Feasibility

Although power control (PC) has been considered in most of the CAC schemes mentioned above for controlling the signal quality in CDMA networks, none of them considered the power allocation feasibility in the admission process. Various CAC schemes used the power allocation feasibility for call admission in CDMA networks. Andersin *et al.* proposed in [25] an interactive CAC scheme, called soft and safe (SAS), that uses the feasibility of the power allocation as the admission criterion employing the distributed constrained power control (DCPC) [45]. In SAS, when a new user arrives, it is allowed to transmit using the DCPC (as active users) but with a limited maximum power that increases gradually. After the power conversion, if the target SIR is achieved, the call is admitted; otherwise, the call is blocked. The main drawback of this algorithm is the relatively long time needed until an admission/rejection decision can be made by the system. A faster algorithm (F-SAS) that uses a single iteration only for power updating is also proposed. Although the second algorithm is faster, it can introduce a considerable amount of errors in the admission decisions. SAS (and its faster version, F-SAS) have been enhanced in [46] to provide a faster and safer (less admission errors) interactive PC-based CAC. In [47] a similar interactive CAC scheme, called distributed power control with active link protection (DPC-ALP), has been proposed. In DPC-ALP, new users increase their power by a small step (δ) while ongoing calls have their SIR higher than the target value by a specified margin value.

In [5] power is updated using the DCPC while the power of the new user is monitored for N iteration. Then, two admission procedures are used. In the first procedure, called transmitted power CAC (TPCAC), the user is blocked if the transmitted power is greater than the threshold value; otherwise, the new user is admitted. In the second procedure, called received power CAC (RPCAC), the received power is used as an admission criterion where the new user is rejected if the received power is higher than a threshold value. It has been shown that RPCAC outperforms TPCAC. TPCAC has been used in [19] in the downlink of a CDMA network. Both total transmitted power per BS and per channel are used as admission criteria at the target cell and its neighbors as well. Three CAC schemes have been compared in [18]: F-SAS, given in [25]; SIR-based CAC, proposed in [9]; and RPCAC, presented in [5] for the uplink in the Manhattan environment along with BS assignment (BSA). It has been shown that RPCAC outperforms other CAC schemes.

In [4] a non-interactive-power-allocation-feasibility-based CAC scheme has been proposed. In this scheme a (centralized) control unit checks the achievable SIR if the new call is admitted, taking into account the path-gain matrix, transmitted power of active calls, and maximum power employing DCPC. If the achievable SIR is higher than the target value, the call is admitted; otherwise, the call is rejected. It should be noted that this scheme, unlike other schemes mentioned above, does not allow the new call to transmit during the admission phase, and the admission decision process is merely non-interactive and based on the SIR calculation at the control unit. The advantage of this approach is that it is faster in reaching the admission decision and more protective of the active calls since these calls do not change their power level during the admission of new calls. Similarly, the authors in [49] proposed a non-interactive scheme that finds the optimum power allocation in WCDMA. The algorithm calculates the optimum power levels that satisfy the outage probability constraints for all users iteratively. Both the inter-cell interference and the intra-cell interference are assumed to follow Gaussian distribution. When a call arrives to the network, the optimum power levels are determined using the proposed power allocation scheme. Then, the constraint of the total power (P_{tot}) is checked assuming that P_{tot} also follows Gaussian distribution. If the user can be assigned the power level without violating the constraint, the user is admitted to the network; otherwise, this call is blocked. A similar approach is proposed in [50] to check the power allocation feasibility as a criterion for admission in WCDMA systems with multiple-classes. This test checks whether there is any feasible power allocation that can achieve the target values of SINR of users in all classes. If feasible power allocation can be found, then further optimized power allocation is sought for higher SINR than the target values.

Transmitted/Received Power

The transmitted/received power can give an indication of the signal quality to be offered to the new call as well as the ongoing calls. Therefore, both transmitted power and received power are employed as admission criteria in CDMA networks. In [26] the 95 percentile of the total received power in the uplink is utilized as a metric or indicator of the interference level in the reverse link of WCDMA systems. When a call arrives this metric is computed for current calls and for the new call (assuming the call is admitted). If both are less than the threshold, it is admitted. It should be noted that the estimated total power includes the estimated effect of the attempting call.

The CAC scheme proposed in [51] uses the total transmitted power in all beams as the admission criterion in a WCDMA network with directional antennas using a binary closed loop SIR-based PC. In [52] the proposed CAC scheme compares the total received power with a pre-specified threshold in a multi-class CDMA system. A single threshold and multiple thresholds (for each class) are used, and it has been shown that the latter is superior in terms of outage probability and it can be used to prioritize some service/classes. Call removal is also included in the CAC scheme if the achievable SIR is less than the target value. In [53] the noise rise, defined as the ratio between total received power and the noise power, is used as the admission criterion in the uplink of WCDMA systems with and without multi-user detection. The noise rise of the home cell, as a relative metric of the interference level, is estimated, and based on its value, it is decided whether or not to admit the incoming call. This approach is extended in [54] where the noise rise in the home cell as well as neighbor cells has to be below the threshold value in order to admit the incoming call. The estimation of the noise rise of the neighbor cells is needed since admitting a new call affects not only the home cell but also the surrounding cells. Hence, the signal quality in the surrounding cells has to be estimated (using the noise rise) before admitting the new call. The noise rise of the neighbor cells is estimated at the home cell using the reported pilot level.

Optimum CAC with Signal Quality Constraints

The signal quality is controlled in this class of CAC schemes by solving the problem as a constrained optimization problem. Such schemes optimize some objective function giving some constraints on signal quality measures. This approach has been used in [55] to maximize the system capacity while maintaining an upper bound of the outage probability and blocking probability. Modified linear programming techniques are used to solve the optimization problem and find the optimum policy. The optimized CAC policy is compared with two other CAC schemes, the fixed number CAC scheme and the interference-based CAC scheme, and results show that the optimized CAC scheme is superior. The same approach is used in [56] to maximize the system capacity in hierarchical cellular structures (consisting of micro/macro cells).

In [27] an optimum CAC policy is employed to minimize the blocking rate of voice calls while maintaining the signal quality in terms of probability of packet error. The CAC policy is based on a Semi-Markovian Decision Process (SMDP). A cost function, which is equal to the number of the blocked calls, is minimized using the value-iteration algorithm. This optimum policy is compared with a threshold CAC policy based on the number of users, and is called the direct admission algorithm. It has been shown that the reduction factor in the blocking probability of the voice calls can be as high as 15 percent due to the use of the optimum admission policy compared to the direct admission algorithm. Similarly, the algorithm proposed in [57] minimizes the blocking probability of one service class while taking blocking rate requirements of other classes and SIR condition as constraints. The problem is then formulated as a Semi-Markovian Decision Process

(SMDP) and solved by linear programming. The SIR constraint takes into account the multiuser detection feature.

The proposed scheme in [58] maximizes a cost function that is equal to the sum (over all cells) of the difference between weighted call admitting probabilities ($1 - P_b$) and weighted dropping probabilities. The chosen weights reflect the relative impact of call blocking and dropping. The optimization problem is subject to constraints on maximum blocking probability and minimum SIR for all users in all cells assuming non-uniform traffic. It is not mentioned how the maximization problem is solved, but the optimum maximum number of users in each cell is found using the derivative of the cost function with respect to the maximum number of users per cell. This implies that the maximum number of users is assumed non-integer. This assumption is not only non-realistic but also might lead to a non-optimum solution, as known from the theory of integer programming.

A joint optimal beam forming, power control, and access point scheme that minimizes the total transmitted power subject to SINR constraints is proposed in [59]. If the system turns out to be infeasible, the most critical users for system feasibility are blocked (removed) one by one until the system reaches a feasibility status. Although results show the proposed scheme enhances the system throughput and blocking rate, this joint optimal scheme seems impractical since the optimization problem has to be solved offline using optimization packages, which cannot be done in real-time systems.

CAC for Controlling the Signal Quality in TDMA Networks

In traditional TDMA networks, a minimum signal quality is guaranteed using a sparse frequency reuse plan (e.g. with a frequency reuse factor of 7 or larger). This approach can guarantee SIR_{min} in a stochastic manner (when shadowing and fading are considered) at the expense of limiting the number of channels per cell. Alternatively, a tight frequency reuse plan (with a frequency reuse factor of 3 or 1) can be employed to increase the number of available channels per cell. In this case, TDMA network capacity is limited by the signal quality (soft capacity) rather than channel availability (hard capacity) in traditional TDMA networks. Therefore, CAC schemes, along with some other resource management techniques, must be employed to guarantee SIR_{min} since cochannel interferers are no longer distant enough from each other. In [60] a CAC scheme has been proposed for fixed wireless networks. The CAC scheme checks all available time slots in the cell and admits the user if at least one time slot has $SIR > SIR_{min}$. If SIR goes bellow SIR_{min} throughout the call duration, the call is reassigned to a different time slot that satisfies the SIR condition.

In [61] two CAC schemes have been proposed for GSM networks with soft capacity and slow frequency hopping. These schemes use the loading factor, defined as the ratio of the number of active calls to the total number of channels, for admission decisions. The first one uses the loading factor in the target cell as the admission criterion. Loading in neighbor cells can influence the admission decision such that if neighbor cells are lightly loaded, higher loading can be admitted in the target cell and vice versa. Hence, spatial averaging of the loading factor is considered in the second CAC scheme. In this scheme, each cell with its six cochannel interferers in the first tier constitutes what is called an interference group, as illustrated in Fig. 2. When a new call is attempted, the average loading factors of all interference groups containing the target cell are checked. If all of them are below the threshold value, the call is admitted; otherwise, the call is rejected. The second scheme that includes spatial averaging of loading factors outperforms the first scheme by increasing the system capacity by 32 percent and 49 percent in uniform loading and hot spot, respectively. This capacity gain is achieved without causing any degradation to the signal quality.

In [62, 63] three CAC policies use the loading factor as the admission criterion to ensure the signal quality in TDMA networks with soft capacity. The first policy compares the loading factor in the target cell with a specified threshold and admits the call only if the loading factor is less than the threshold value. Spatial averaging of loading factors in the target cell and its first tier neighbor cells is used in the second CAC policy. The spatial averaging is extended more in the third CAC policy to consider loading values in the second tier as well. In this policy, the threshold value of the average loading factor of the first tier is adjusted according to the value of the average loading factor in the second tier. When the cells in the second tier are lightly loaded, the average loading factor in the second tier is small, and as a result more loading can be admitted in the first tier by increasing the threshold value of the average loading factor of the first tier and vice versa. It has been shown that the third CAC policy is the best in terms of the blocking rate, but nevertheless it requires more information transfer between BSs. Time averaging of loading factor has been utilized in [64] to increase the system capacity in TDMA systems with soft capacity and slow frequency hopping, and it has been shown that a considerable increase in system capacity (more than 30 percent) can be achieved by using the time-averaging of the loading factor as the admission criterion without causing any significant degradation to the signal quality in terms of the outage probability.

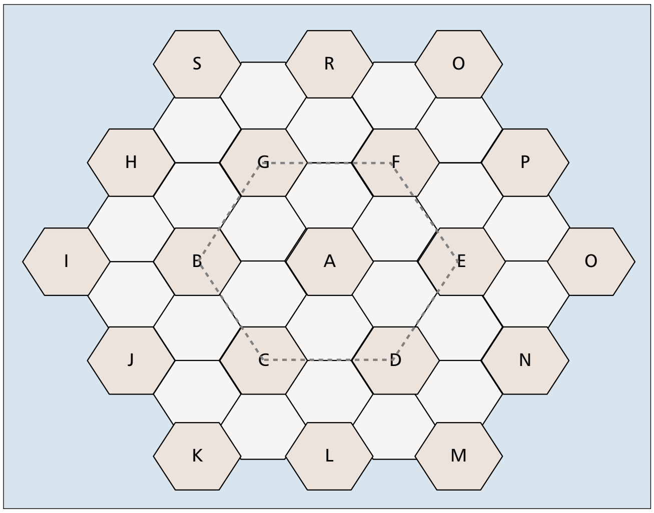
CAC for Controlling Handoff Failure Probability

In order to control the handoff failure probability (P_{hf}), certain measures have to be employed to prioritize handoff calls over new calls since it is commonly accepted that dropping an existing call is more annoying to the user than blocking a new call. Table 3 lists the various approaches used to control the handoff probability in wireless networks. In all approaches there is a tradeoff between reducing handoff probability and new call blocking probability

In the following subsections, the CAC approaches listed above in Table 3 are discussed in some detail based on the published work in the literature. Hybrid CAC schemes and handoff queuing are discussed later.

Guard Band Policy

The guard band policy has been proposed by Hong and Rappaport in [65]. As shown in Fig. 3a, this technique keeps a certain amount of channels to handoff calls only while the rest of the channels can be shared by both new calls and handoff calls. Hence, handoff calls are given higher priority over new calls, and as a result the reduction in the handoff probability comes at the expense of higher blocking rate. Therefore, the guard band (number of channels) reserved for handoff calls must be properly chosen as a tradeoff between new call blocking probability and handoff dropping probability. However, even if the guard band is chosen properly to control both P_b and P_{hf} based on certain assumptions for the traffic load parameters (new and handoff call arrival rates), this does not guarantee P_b and P_{hf} since the traffic load parameters are variable. Guard band policy is used in the CAC scheme proposed in [73] and [18] for multi-service mobile networks based



■ **Figure 2.** *Interference groups with cluster size of 3. Interference group of A = [B, C, D, E, F & G]; interference group of B = [C, A, G, H, I & J]; interference group of C = [A, B, J, K, L & D]; interference group of D = [A, C, L, M, N & E]; interference group of E = [A, D, N, O, P & F]; interference group of F = [A, E, P, Q, R & G]; interference group of G = [A, F, R, S, H & B].*

on a complete sharing policy of all classes. Analytical (exact and approximate) methods for analyzing guard band policies are provided in [18].

Dynamic guard band schemes that adapt the amount of reserved channel according to some traffic parameters have been proposed in [21, 74, 75] and shown to outperform the fixed guard band.

It has been shown in [12, 13] that the guard band policy can minimize a linear objective function of P_b and P_{hf}. An enhanced version of guard channel policy, called fractional guard channel policy (FGCP), has been proposed in [12, 13] and proven to be optimal in minimizing P_b with a hard constraint on P_{hf} and minimizing the number of needed channels with a hard constraint on both P_b and P_{hf}. In FGCP and as illustrated in Fig. 3b, a new call is admitted by a probability β_i which is a decreasing (or, more accurately, non-increasing) function of the cell state (i) defined as the number of occupied channels, while a handoff call is admitted as long as there is a free channel.

A special case of FGCP (limited FGCP) is shown to be more effective than the basic guard band policy in minimizing P_b and the number of needed channels while holding the constraint on P_{hf} [12, 13]. In the limited FGCP, as shown in Fig. 3c, there are three possible admission probabilities for new calls (1, β, 0) where β < 1. The first value (unity) is used as long as the cell state (i) is less than T; the second value is used when the cell state (i) is equal to T; the third value is used when the cell state (i) is greater than T where T is a design parameter. FGCP is extended in [76] to the case of multiple classes. Two versions have been proposed to prioritize handoff calls over new calls and to prioritize some services over other services. In the first scheme, the admission probability of a new user belongs to a certain class, P_{ad_n}, and is a non-increasing function of the total number of busy channels (by all classes). In the second scheme P_{ad_n} is a non-increasing function of the number of busy channels in this particular class. It is obvious that the latter scheme provides more fairness among different classes, although the trunking efficiency is higher for the first scheme.

In [14] the guard band is calculated as the sum of fractional bandwidth (occupied bandwidth divided by the number of neighbors) in neighbor cells multiplied by the fractional parameter (f_i) which reflects the fraction of potential handoff traffic to the target cell from its neighbor cells and weighted by $(1 + C_o/C)$, where C_o is the amount of occupied bandwidth and C is the total bandwidth in the target cell. This weight is used to increase the guard band when the system gets highly loaded so P_{hf} can be minimized.

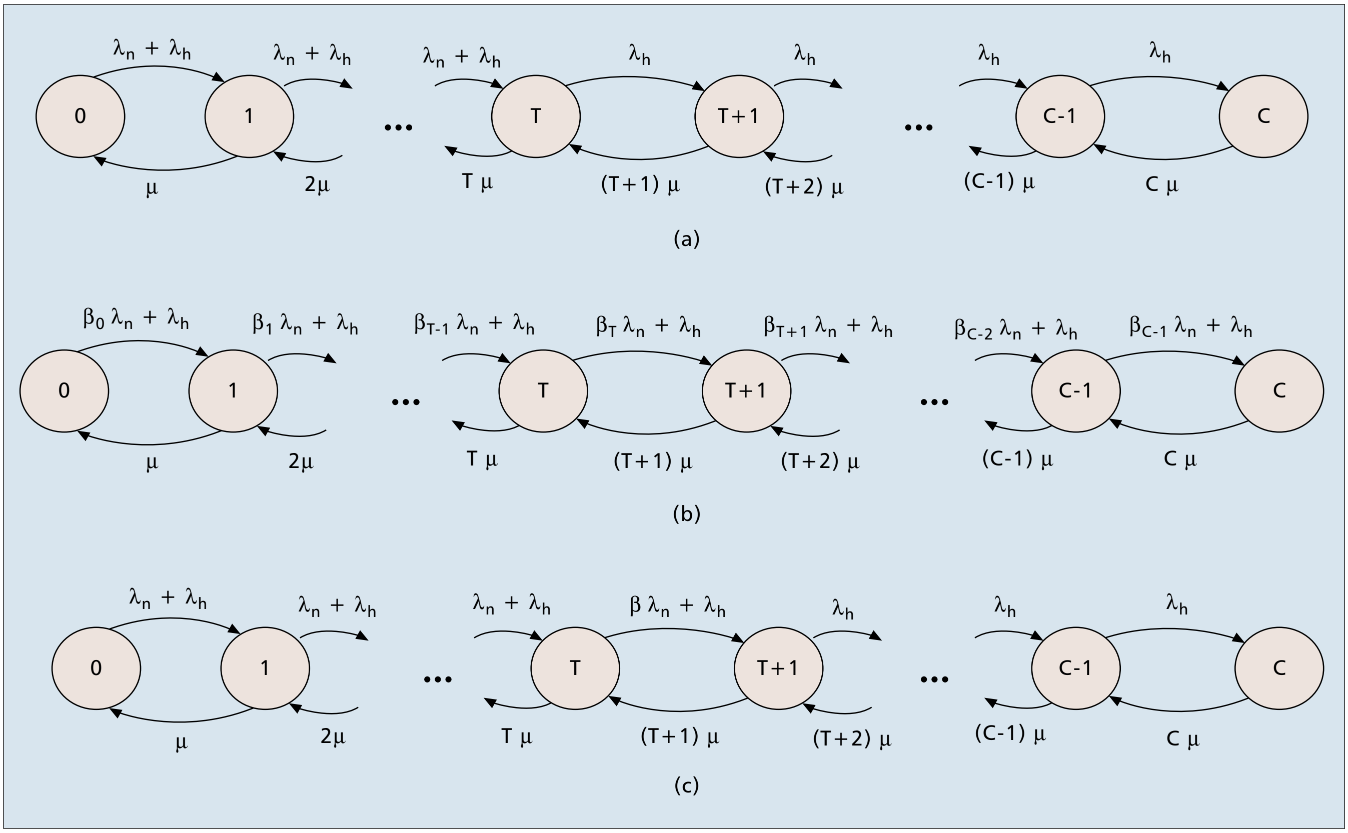
A new call bounding scheme has been proposed in [77, 78] in which a threshold is used to limit the number of new calls in the cells. Handoff calls are only blocked if all channels are occupied. This scheme, along with guard band policy and FGCP, has been analyzed taking into consideration the different distribution of call holding time of new calls and handoff calls.

A hybrid scheme of guard band policy and channel reassignment has been proposed in [79] to minimize P_{hf} while maintaining high utilization. In this scheme the number of guard channels is dynamically adapted as a function of channel reassignment requests.

In [80] calls are admitted depending on the resources availability and their priority. Guard band is used for handoff calls. If the guard band is not enough, preemption and deprivation

Approach	Brief explanation	Seminal work	Comments
Guard band	A certain amount of resources are reserved exclusively for handoff admission.	[13, 65]	Leads to a high blocking probability
Loading in home cell and neighbor cells	New call is admitted if loading is less than a threshold value in home cell and neighbor cells.	[66–69]	Information exchange is needed
Resource availability in home cell and neighbor cells	New call is admitted if the needed resources are available in home cell and neighbor cells.	[70]	Information exchange is needed
Estimating handoff failure probability	Handoff failure/overloading probability is estimated and used as the admission criterion.	[10, 71, 72]	Based on some assumptions or approximations
Optimum CAC with handoff failure probability constraint	An admission policy is determined by optimizing some objective function subject to P_{hf} constraint.	[13]	Usually solved by Markovian Decision Process
Lower interference threshold for new calls	New calls and handoff calls are admitted based on the interference level. However, new calls must have lower interference level.	[37]	Used to control signal quality and P_{hf} in CDMA networks

■ **Table 3.** *Various approaches of CAC for controlling handoff failure probability.*



■ **Figure 3.** *State transition of: (a) guard channel policy; (b) fractional guard channel policy; (c) limited fractional guard channel policy.*

are used. Preemption is used to remove non-real-time calls on the guard band if there are not enough resources for real-time handoff calls. If there are no non-real-time calls on the guard band, preemption cannot be used and deprivation is used instead by reducing the resources allocated to VBR and ABR calls. A similar policy has been proposed in [81]. A fixed amount of resources is reserved for handoff calls. When a new (or handoff) call arrives to the cell and finds no resources available in the cell, a borrowing scheme is utilized by reducing resources allocated to existing calls in a fair and gradual way to accommodate the arriving call.

A guard band CAC policy is employed in [40] to prioritize voice handoff calls in a CDMA system. In this scheme the number of users is used as a criterion for admission, and as a result a higher threshold for the number of users is used for handoff voice calls. Handoff data calls are queued if the number of users exceeds the threshold value.

Loading in Home Cell and Neighbor Cells as an Admission Criterion

One way to control the handoff probability is to take loading information in neighbor cells into account in the admission process. This is because loading information in neighbor cells can reflect the admissibility of potential handoff calls from the target cell (cell of the new incoming call) to its neighbor cells since the higher the loading in neighbor cells, the higher the probability of handoff failure and vice versa. This loading information also indicates the amount of potential handoff calls from neighbor cells to the target cell. For instance, the number of users per cluster is used as a CAC criterion for single-service real-time traffic in [66]. Similar CAC schemes have been proposed for data traffic, multiple classes of traffic, and wireless ATM networks in [7, 67, 68], respectively.

In [68, 69] a virtual tree architecture has been introduced to establish virtual connection between the mobile users and the target BS in addition to all BSs that the user is likely to visit. Although such CAC schemes can reduce P_{hf}, congestion still can take place in some cells even if the number of users per cluster is still below the threshold value. Therefore, the use of double threshold CAC has been proposed in [82] to limit the number of users per cell and per cluster as well. The double-threshold CAC is shown to outperform the cluster-based CAC in terms of achieved throughput, call success probability, and reduction in P_{hf}. Instead of using two thresholds, one per cell and one per cluster, [83–85] have proposed a CAC scheme, called weighted sum scheme (WSS), that uses a weighted sum of a number of users in the cluster (or even all surrounding cells) including the target cell. Larger weights are given to the target cell and first-tier neighbor cells, while smaller weights are given to farther cells.

The number of users in the target cell and neighbor cells is used in [8, 86] to determine the maximum number of new calls that can be admitted in the target cell. This number is determined using the estimated overloading probability (P[number of users > N], where N is the number of channels per cell) as an approximation of P_{hf}. A handoff call is admitted as long as there is a free channel. This scheme can be considered as an adaptive version of the new call bounding scheme proposed in [87], where the number of users in neighbor cells is used to adapt the new call bound. This scheme has been analyzed in 1d and 2d cellular structure in [8] and [86], respectively, and it has been shown that it outperforms the guard band policy.

However, Gao and Acampora have shown in [87] that cluster-based CAC does not improve the system capacity and a simple CAC scheme that uses the guard band concept can be as efficient as cluster-based CAC schemes if not more efficient with the advantage of reducing complexity.

Resource Availability in the Home Cell and Neighbor Cells

In multiple-service wireless systems with different resource requirements, P_{hf} can be minimized by ensuring that the required resources for a new call will be available during the call duration. Then the required resources might (or might not) be reserved to this particular call in the target cell as well as a neighbor cell. When resources are reserved, this approach can be considered as a modified version of the adaptive guard band policy where the guard band is adapted according to the required resources by already arrived calls.

A resource-reservation-based CAC has been proposed in [70]. This scheme checks whether the required bandwidth in the cell and neighbor cells is available for real-time traffic. Non-real-time new calls are admitted if the target cell only has the required bandwidth. Handoff is accepted if the minimum bandwidth is available in the home cell, and other cells can reserve the bandwidth for real-time traffic. Non-real-time handoff calls are accepted if any bandwidth is available. Two bandwidth reservation schemes are analyzed in [70]. The first scheme reserves in each cell the sum of required bandwidth by all real-time new calls in all neighbor cells. The second scheme utilized statistical multiplexing and reserves only a portion of the sum of the required bandwidth. Results in [70] show that resource reservation is effective in reducing P_{hf}. A similar CAC scheme has been discussed in [89] and [90] but with bandwidth reservation in neighbor cells for real-time calls if the new real-time call is classified as a departing user (based on user location prediction); otherwise (if the new call is classified as local call), bandwidth reservation is performed in the target cell only. Non-real-time calls are admitted based on the buffer space in the target cell.

Reservation-based CAC schemes that reserve bandwidth in some of the neighbor cells with high probability of receiving handoff traffic from the target cell have been proposed in [20, 91–95]. In [91] the probability of receiving handoff traffic from the target cell is estimated using the history of handoff traffic from that cell to its neighbor cells. In [92, 93] the probability of receiving handoff traffic from the target cell is predicted using mobility information of new calls, which is not easy to implement in reality. The proposed scheme in [20] considers the admission in the downlink of a WCDMA system. In this CAC scheme, each cell calculates the reserved bandwidth for anticipated handoff calls from neighboring cells. The probability of call handoff to a certain cell is estimated from the handoff history in the serving cell. Then the reserved bandwidth in any cell is updated as the sum of the required bandwidth by anticipated handoff calls weighted by the probability of call handoff probability to this particular cell. When a new call arrives, the bandwidth reservation is checked in the home cell and all neighboring cells that failed to reserve the target bandwidth in the previous admission check. It is noteworthy that the home cell checks the bandwidth availability, taking into account the required bandwidth by the new call, the used bandwidth by existing users, and the reserved bandwidth of anticipated handoff calls, while neighbor cells check the bandwidth availability, taking into consideration the used bandwidth by existing users and the reserved bandwidth for anticipated handoff calls only. The two CAC algorithms in [94] and [95] assume perfect mobility estimation. While the former assumes that the next cell only is known, the latter assumes that the whole call trajectory is known a priori. In both algorithms, cells expected to be visited in the future by the new call increase the reserved bandwidth by the amount of required bandwidth of the new call. However, in [94] the bandwidth availability is checked only in the home cell, while in [95] the bandwidth availability is checked in the home cell and all cells to be visited as well, and the call is admitted only if all cells can reserve the required bandwidth. Results show that both schemes eliminate handoff failure but at the expense of high blocking rate [96].

In [78] the proposed scheme checks the availability of bandwidth in the home cell only (as in [94]). However, unlike the scheme in [94], the bandwidth is reserved in each cell using information about users' mobility (cell residence time distribution) and directivity in neighboring cell.

Resource-reservation-based CAC to guarantee QoS parameters (packet delay and delay jitter) in both CBR and VBR traffic in wireless ATM has been proposed in [6, 97, 98]. When a new call (CBR or VBR) arrives, QoS bounds are checked, taking into consideration available resources after excluding resources used by active calls and resources reserved for potential handoff calls. If QoS performance parameters can be guaranteed, the new call is admitted. Handoff calls are admitted in the same way without excluding the resources kept for potential handoff calls.

In [99] the admission condition for new calls is based on the resource availability such that the system is inside the schedulable (or the admissible) region in terms of the number of users and arrival rate. However, even if the system is in the admissible region in terms of number of users but not inside the admissible region in terms of the arrival rate of handoff calls, the incoming call still can be admitted, especially the real-time traffic. Likewise, a stringent admission condition is imposed on new calls in [100] such that if there are not enough resources for all components of a new multimedia call, the call is blocked. Handoff calls, however, can be admitted even if some components with lower priority will be dropped. Handoff calls can even stay in the old cells to avoid call dropping.

In [101] when a handoff arrives and does not find enough resources, data users are instructed by the BS to reduce their rate to accommodate the handoff call. A handoff call is only rejected if the reduced rate is less than a predefined minimum rate (r_{min1}). Similarly, new calls are admitted even if there are not enough resources by reducing the transmission rate of data users with a minimum rate (r_{min2}). By setting the minimum rates such that ($r_{min2} > r_{min1}$), handoff calls are prioritized over new calls.

Estimating Handoff Failure/Overloading Probability

Blocking new calls that have high probability of being dropped later on is an efficient way to control P_{hf} while maximizing the resource utilization. Hence, many CAC schemes have adopted this approach for reducing P_{hf}. In [71, 72] the shadow cluster concept has been introduced as a framework for wireless multimedia to estimate future resources requirements in cells likely to be visited by the new calls based on user mobility information, as shown in Fig. 4. Based on the resource estimation and mobility information, call survivability is determined as an indicator of the success of call completion, taking into account potential handoff events of the new call to neighbor cells. The shadow cluster concept has been adopted in [102] where the application semantics (loss profile) and delay profile have been taken into account to improve the performance and resource utilization.

Although the shadow cluster concept is effective in reducing P_{hf}, it is based on the availability of mobility and call duration information, which is infeasible in reality. Similar schemes have been proposed, with the difference that the user transition from the target cell to neighbor cells estimation is assumed to be predictable from long-term statistics of the net-

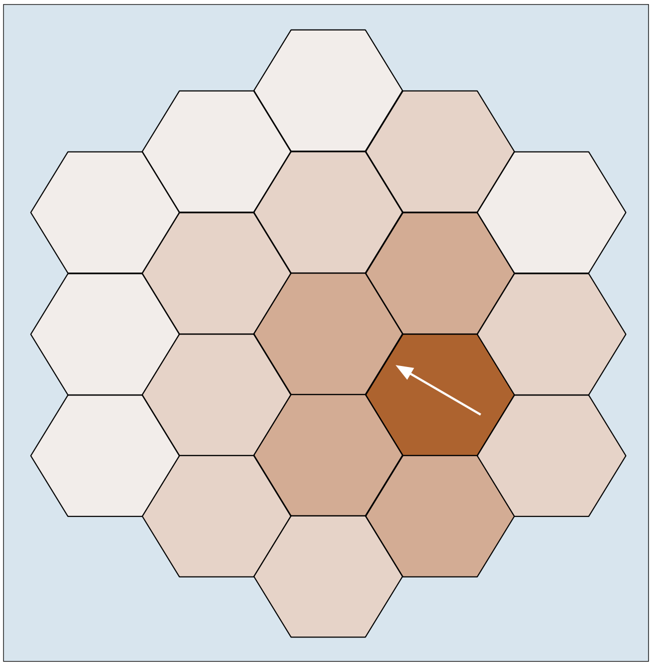


Figure 4. *Shadow cluster formed by a mobile terminal.*

work [103], a macroscopic mobility model [104], or by training a hidden Markov model (HMM) [105], rather than mobility information as proposed in the shadow cluster concept. In [103] the CAC scheme uses the overall handoff probability, which is a weighted sum of handoff failure probability in all cells as the admission criterion.

An index that roughly reflects the P_{hf} is used as an admission criterion in the probability index scheme (PIS) proposed in [83–85]. This index is determined using approximations that allow the network to be modeled as a queuing network that can be analyzed by the Jackson theorem [106]. P_{hf} is approximated by the overloading probability (Pr[number of users > N], where N is the number of channels per cell) and used as the admission criterion in wireless ATM networks in [107–110] using Gaussian approximation for the number of users, as in [66, 86]. In [10] P_{hf} is used as the admission criterion in multiple-class wireless network. The amount available for each class is updated using traffic load measurements to keep the relative blocking probability at a specific value. If there is enough bandwidth based on the two conditions, the call is admitted; otherwise, it is rejected. Handoff calls are admitted using complete sharing (CS).

The handoff failure probability (P_{hf}) is estimated in [111] using diffusion equation and inter-cellular transition probabilities. In this scheme, P_{hf} is estimated as a function of the admission probability. Hence, the admission probability can then be calculated given the required P_{hf}. Then users are admitted to the system in a stochastic manner using the admission probability. The admission probability is updated according to the variation in the traffic conditions.

In [112] the handoff failure rate is measured by the MSC. Then the measured dropping rate is used to adapt the admission threshold in the cells controlled by the MSC. If the measured dropping rate exceeds the maximum allowed value, the admission threshold is decreased and vice versa. Furthermore, the handoff failure rate is controlled by involving neighbor cells in addition to the target cell in making the final admission decision. This is implemented by computing the final admission parameter as a weighted sum of the decision parameter of the neighbor cells and the target cell as well. Then the final admission parameter is compared with the adaptive threshold and the call will be admitted if the final admission parameter exceeds the admission threshold. A similar algorithm is employed in [113]. In this algorithm, the resource-based admission threshold of new calls is adapted in each cell according to the short-term and long-term measured handoff failure rate. Handoff calls are admitted as long as there are enough resources. Although this algorithm can guarantee a maximum P_{hf} in the average sense throughout the whole network, it is found that this approach might lead to inter-cell unfairness, which means that some cells might have low P_{hf} while other cells might experience high P_{hf}. This unfairness has been dealt with using two different approaches. The first approach considers the resource availability in the home cell and the neighboring cell as well. The second approach considers the resource availability in the home cell only, but the changes in P_{hf} cause changes in the admission threshold not only in the home cell but also in the surrounding cells. Results showed that the second approach is superior to the first approach in terms of P_{hf} and bandwidth utilization.

Bandwidth reservation is performed in wireless multimedia networks as a function of user mobility and handoff load, as proposed in [114–117]. When a new call arrives, overload probability (P_{ov}, probability-required resources exceed unused resources) is checked in the cell and its neighbor cells. P_{ov} is checked in the target cell and the neighbor cells as well. If $P_{ov}<$ threshold value (P^T_{ov}), the call is admitted; otherwise, it is rejected. Handoff calls are always admitted unless the available bandwidth is less than the required bandwidth.

Optimum CAC with P_{HF} Constraints or Prioritization

P_{hf} is controlled in some CAC schemes by considering the admission process as a constrained optimization problem where the objective can be maximizing the resource utilization, maximizing a revenue function, or minimizing the blocking probability subject to a constraint on the P_{hf} and maybe other constraints such as P_b or packet delay [118]. Finding the optimum admission policy is usually modeled as a Markov Decision Process (MDP), and then linear programming is used in [3, 11, 12, 119–123] to find the best admission policy at each state (number of users per cell). Since the problem is inherently non-linear, some techniques such as separable programming are used to solve the problem by linear programming [11, 119, 120, 122].

It has been shown in [120, 122] that the optimum CAC policy that maximized the revenue function while maintaining the P_{hf} constraints is FGCP. FGCP is also proven to be the optimum policy in [12] if the objective is minimizing P_b or the number of required channels. In wireless networks with a large number of users and cells, the problem size makes the use of MDP impractical. Therefore, genetic algorithms have been proposed as an alternative to find suboptimal CAC policies, but with much less computational effort. A genetic algorithm is used in [124] to find a near-optimal CAC by minimizing a linear combination of P_b and P_{hf} with a larger weight given to P_{hf} in the fitness function. It has been shown in [124] that the near-optimal CAC based on genetic algorithms has a very close performance to the optimal algorithm found by a Markov decision process (MDP). Similarly, a genetic algorithm is used in [125] to maximize the resource utilization of multimedia multiple-class resource allocation schemes while maintaining a hard constraint on P_{hf}. Although the achieved utilization is a little bit less than the optimum value of MDP (by less than 10 percent), the reduction in the computational burden justifies this insignificant reduction in the resource utilization.

HIGHER INTERFERENCE THRESHOLD FOR HANDOFF CALLS

It is possible to prioritize handoff calls by using stringent conditions on new calls. Following this approach, P_{hf} is controlled in CDMA networks by prioritizing handoff calls in [37]. Two threshold values of the interference levels are employed as the admission criterion for new and handoff calls. The threshold value of the handoff calls is chosen higher than that of new calls. A similar approach has been adopted in [41]. Soft handoff (SHO) calls have been given a higher threshold (of the cell loading value) than that given for new calls. This concept is called "*soft guard band*" since it is similar and has the same function as the guard band concept proposed in bandwidth-limited networks, but in CDMA networks that have soft capacity (interference-limited). When non-real time data users are considered, SHO voice users are prioritized by admitting them even if the interference threshold is exceeded by lowering the interference through the interference suppression of non-real time data users [37]. The interference suppression is performed by switching data users off and on periodically.

HYBRID SCHEMES

Sometimes a hybrid admission criterion is needed to achieve the QoS guarantee. For instance, [126] proposed the use of a hybrid admission criterion of the probability index schemes (PIS) and the weighted sum scheme (WSS), since the former might lead to congestion in the target cell when other cells are lightly loaded. Combining DCA and a CAC schemes is another example.

In [127] the estimated call dropping rate (CDR) is used as an indicator of the network loading. At low CDR, the new call is admitted as long as it can be accommodated by the DCA. If the CDR is high, the call is admitted if the number of the required channels is less than $1/n$ of the number of available channels at the cell, where $n > 1$ and can be adaptively adjusted based on the traffic conditions and network loading. Handoff calls are always admitted, provided that the DCA can accommodate them.

In [128] the CAC scheme uses the number of users and the moving average of the degradation ratio (number of users with rates less than target rates) as the admission criterion. In order to avoid loading fluctuation (because the moving average does not reflect the current status quickly), the number of users is checked first. If the number of users is lower than a lower threshold (t_{min}), the call is admitted; if the number of users is between the lower threshold (t_{min}) and an upper threshold (t_{max}), the degradation threshold is used as the admission criterion.

UPPER BOUND OF CAC PERFORMANCE

Upper bounds of the performance of CAC schemes that prioritize handoff calls are provided in [17, 129]. In [17] the benchmark is developed using a CAC scheme that has perfect knowledge of the wireless network, including future handoff events. This scheme estimates the potential gain/loss in bandwidth utilization due to admitted new calls and decides accordingly to admit/reject the call. In [129] a CAC policy has been determined that maximized the efficiency defined, which is defined as the achieved throughput divided by total available bandwidth. This CAC policy turned out to be a special case of limited FGCP where the threshold is placed at the mean occupancy and the admission probability is proportional to the mean occupancy. This scheme is found based on the assumption that the system controls the new call arrival rate and knows in advance the system efficiency. Although these schemes proposed in [17, 129] are not realistic, they are of paramount importance since it helps in analyzing the performance of CAC schemes in this category.

HANDOFF CALL QUEUING

Queuing handoff calls has been proposed in various papers to control P_{hf}. For instance, it has been shown in [65] that combining handoff call queuing with the guard policy can considerably reduce P_{hf} (by more than 60 percent at high loading values) compared with the guard band policy without call queuing. Queuing handoff data calls has also been proposed in [40] to minimize P_{hf}.

CAC FOR CONTROLLING PACKET-LEVEL QOS PARAMETERS

In order to ensure the packet-level QoS parameters such as packet delay, delay jitter, or packet dropping rate, in [6, 98] the proposed CAC scheme estimates the packet delay and delay jitter based on the available resources in multiple-class wireless ATM networks. If both packet delay and delay jitter can be guaranteed, the call is admitted; otherwise, it is rejected. In [130] the admissible region of real-time VBR services is determined. The admissible region is calculated based on constraints on the packet dropping probability. The admissible region can be used for call admission by examining the network state (when a new call arrives) to determine whether it is inside the admissible region. It should be noted that the admissible region depends on the used scheduling scheme.

In [131] a CAC scheme has been proposed to control the packet dropping rate for video conference services over the uplink of high-capacity wireless systems. Different quality levels are provided using various layers and encoding techniques (MPEG4 and H.263). When a new call arrives, the effective bandwidth of all existing users, including the new call (using the highest quality level), is determined. Then the new call is admitted only if the total effective bandwidth is less than the system bandwidth. If the condition is not satisfied, the call reduces the quality level and tries to gain access again. If the total effective bandwidth is still higher than the system bandwidth, existing users start to reduce their quality level one by one. If all users (new and existing) are reduced to the lowest quality and still the effective bandwidth is higher than the system bandwidth, the new call is blocked. The system also checks the dropping rate of existing users every minute. If the droping rate of any user exceeds the maximum rate (10^{-4}) on two consecutive checks, a new cycle of quality reduction is initiated starting from the last entered user.

CAC FOR TRANSMISSION RATE CONTROL

CAC schemes can ensure a minimum transmission rate either by limiting the network loading (as in [7, 67, 132]); by minimizing the transmission rate degradation (defined as the condition of having the transmission rate below the minimum rate) as in [128, 133], or by estimating the allocated transmission rate as an admission criterion (as in [101]).

In [7, 67] the number of users per cluster is limited by a maximum value such that a minimum transmission rate can be offered to all admitted data users even when they move to any of the neighbor cells. The proposed scheme in [132] limits the number of users in the cell such that all existing and new (new and handoff) calls are allocated at least the minimum rate. Handoff users are admitted first (to minimize handoff failure probability), then new calls are admitted based on resource availability. If there are not enough resources and some users have a higher rate than the declared minimum values, resource reduction takes place such that new calls can be accommodated. Linear programming is used to minimize the resource reduction and to maintain fairness among users. The linear programming model is solved using artificial neural networks.

The transmission rate degradation probability, measured by the time average of the transmission rate degradation indicator, is used in [18, 133] as the admission criterion. If the degradation probability is less than a threshold value, the call is admitted; otherwise, the call is rejected. A CAC scheme that admits calls based on resource availability has been proposed in [101]. If there are not enough resources, data calls reduce their transmission and the incoming call is admitted if the reduced transmission rate is higher than a minimum value; otherwise, the call is rejected. In [134] the CAC scheme ensures that average and peak transmission rates for real-time traffic and average throughput for non-real-time traffic can be guaranteed. This is achieved by estimating the maximum and average loading values.

Revenue-Based CAC Schemes

When a call admission is requested, this represents a potential gain to the network revenue because of the expected reward due to the resource utilization. Meanwhile, the incoming call might cause congestion and degradation in the resources allocated to the already admitted calls, which in turn can cause a reduction in the network revenue. Therefore, the CAC policy can play a major role in optimizing the wireless network revenue. In [3, 11, 119, 135] the maximum number of users of each class to be admitted in a multiple-class wireless network is derived offline by solving the revenue maximization problem using linear programming. The degradation in the resource utilization and the dropping probability are taken into account as constraints in the optimization problem. Then a threshold-based CAC scheme uses the maximum number of calls per class, which is determined offline, to admit/reject incoming calls. The revenue is modeled as a linear function of the network state (the number of users of each class). In [79] the proposed CAC scheme maximizes the revenue by minimizing the penalty incurred by dropping an existing call and carrying out a channel reassignment.

A revenue-maximization CAC/pricing policy has been proposed in [136]. In this scheme a pricing parameter, called bandwidth market price (BMP), is defined as the revenue due to the transmission of 10^9 bits of traffic using 1 kb/s of network resources. BMP is determined based on the network loading and QoS requirements to maximize the network revenue. A new call is admitted only if the expected revenue by admitting this call is higher than the current revenue by a certain margin. In [137] revenue is optimized by assigning different priorities to different classes based on the expected revenue of each class. Then calls are served based on the resource availability and the revenue-based priority levels. An integrated pricing/call admission policy has been proposed for voice service in [138]. An optimum new call arrival rate that maximizes the aggregate user satisfaction is first determined. Then the pricing policy is used to provide a negative incentive to incoming new calls by charging new incoming calls at a higher rate when the new call arrival rate exceeds the optimum rate. Handoff calls are charged at the same rate as their originating instants. Results show that the proposed pricing scheme can maximize user satisfaction and increase the network revenue. However, positive incentive for encouraging users to use the network resources when the network is under-loaded has not been addressed in this article.

CAC for Service/Class Prioritization

Prioritizing service/class can be performed by using a different admission criterion for each class such that the class/service with lower priority will have more stringent admission rules. For instance, calls are admitted in [52] based on the received power level with three possible prioritization schemes. The first scheme gives higher priority to voice service by using a higher power level threshold than that of data service. Conversely, the second scheme uses a higher power level threshold for data service than that of voice service to prioritize the data service. Finally, the third scheme uses the same threshold for both services. Results show a significant difference in the QoS (in terms of P_b) provided by each prioritization scheme to the two offered services. For example, the first scheme achieves the lowest P_b for voice service but the highest P_b for data service.

In [39, 40, 139, 140] real-time (or voice) service is prioritized over non-real-time (data) service by using a larger maximum number of users for voice service than that of data service. This is extended in [139] by proposing the preemption of some data calls (by queuing them) if no resources are available to the incoming voice calls. In addition to preemption, deprivation (by reducing the resources of some data calls) is also proposed in [80] to give more priority to voice calls. In addition to the exclusively designated resources for each service, a shared band is proposed in [140]. The shared band can be used by either class of service depending on the traffic dynamic variation.

Prioritizing different classes and different services is considered in [6, 98]. Services are ordered according to their priority and QoS requirements such that CBR has the highest priority, followed by VBR, and finally ABR. Meanwhile, there are different classes for each service and these classes are ordered according to their priority. Resources are reserved to classes/services with higher priority and then to those with lower priority. If the incoming calls find that the reserved resources for its service/class are not enough to achieve the required QoS (packet delay and delay jitter), the call is rejected.

In [141] four levels of priority (high-priority voice, high-priority data, low-priority voice, and low-priority data) are offered by using four dynamically adjustable resource availability thresholds for call admission of two priority levels of both voice and data services. The CAC scheme in [99] prioritizes voice service by using a higher maximum number for voice service than that for data service at the first level of the proposed CAC scheme. At the second level, the probabilistic call admission decision uses higher admission probability for voice calls than that assigned for data calls. Adaptive prioritization schemes have been proposed in [137]. The service priority is a function of the transmission rate required by each service (lowest rate first and highest rate first), maximum delay (services with higher delay tolerance are giving lower priority), and revenue optimization (services with higher revenue are given higher priority). The priority levels are adapted based on the resource availability and traffic characteristics.

CAC for Fairness

Fairness can be achieved by monitoring either the resources allocated to each class [142] or achieved QoS [10]. In [142] the CAC scheme uses a resource-sharing policy called virtual partitioning with priority (VPP). In VPP the priority of each class is reduced if this class is overloaded. The admission condition is given by checking the condition ($\Sigma(b.n) < C\text{-}b\text{-}t$), where b is the needed bandwidth, n is the number of users in each class, C is the total bandwidth, and t is a prioritization parameter that indicates whether this class is overloaded or not. It has been shown that VPP can achieve high multiplexing gain as in the complete sharing policy at light loading values. Meanwhile, VPP achieves high fairness as complete separation policy. In [10], when a new call arrives the total needed bandwidth required (one step ahead) to serve the active calls in addition to the new call (to keep P_{hf} < threshold) is predicted. The available bandwidth for each class is updated using traffic load measurements to keep the relative blocking probability at the required values. If there is enough bandwidth, the call is admitted; otherwise, it is rejected. Handoff calls are admitted using complete sharing policy.

Fairness among users with different mobility characteristics in WCDMA systems is analyzed in [143]. It has been shown that average received power or SIR-based CAC schemes are unfair to stationary users since their received power or SIR have slow variation, and as a result, if a user is in an unfavorable location they will be blocked or dropped. On the other hand, the received power or SIR of users with high mobility characteristics has fast variations; hence, users with high mobility are rarely blocked or dropped. In order to enhance the fairness, a new scheme has been proposed. This scheme uses the average value of SIR in two of the last three frames (after discarding the lowest SIR) as the admission criterion. It has been shown that call dropping and blocking probabilities are distributed (almost) evenly among mobility classes (stationary, pedestrian, and vehicular).

Emerging Trends and Future Research Issues

The proliferation of the Internet and the internetworking protocol (IP) technology has paralleled the vast growth of wireless and mobile communication systems in the last two decades. Although the two domains (the Internet and wireless networks) were kept separate, this is currently changing with the adoption of IP in 3G and beyond wireless networks. Since IP is inherently unreliable, the QoS provisioning (particularly in wireless networks) requires additional measures and schemes for traffic control (classification and prioritization) and resource management (allocation and reservation).

The Internet Engineering Task Force (IETF) has proposed techniques such as the Reservation Protocol (RSVP), Integrated Services Protocol (IntServ), and Differentiated Services Protocol (DiffServ) for QoS provisioning in IP networks. In RSVP, required resources are reserved in all nodes along the whole path from the source to destination nodes. While IntServ uses RSVP to reserve the amount of resources that suits the type of service, DiffServ on the other hand does not perform any resource reservation and it classifies packets into one of a few predefined classes [144]. These protocols, however, must be equipped (integrated) with admission control mechanisms to ensure the availability of enough sources in terms of bandwidth and buffer space, particularly for sessions belonging to a better-than-best-effort service, namely, the guaranteed and controlled-load classes. In order to guarantee end-to-end QoS, the wireless admission control in the wireless IP paradigm has to consider resource availability over the radio access network, in the subnet, and in the core IP network as well. Furthermore, the admission problem has to consider the implications of user mobility not only from one cell to another but also from one subnet to another.

Figure 5 shows a simplified architecture of wireless IP networks. The gateway router is responsible for connecting the radio access network to the subnet, while the bandwidth broker is responsible for the resource allocation and admission control based on the service-level agreement (SLA) [144]. It is worth noting that the admission control here is performed at the session/flow level rather than the call level since efficient utilization of system resource has to deal with sessions/flows rather than calls due to the possibility of having multiple sessions/flows per connection and the intermittent nature of the IP traffic.

A framework for resource-based admission control in wireless IP networks has been provided in [145]. The proposed admission policy is measurement-based. Two techniques are employed in [145] for P_{hf} control. The first technique gives handoff requests a higher priority by serving them before the new requests, while the second technique reserves a certain percentage of total resources solely to handoff requests, as in the guard band policy [65]. Results show that in most cases the first scheme outperforms the second scheme in terms of blocking and dropping rate. However, results also indicate that admission control alone is not enough to guarantee QoS in wireless IP networks, and thus traffic management schemes such as traffic shaping should also be considered.

The provisioning of QoS in wireless IP taking user mobility into consideration has been analyzed in [146–148]. In [146] a virtual admission control is performed in advance (before handoff takes place) in cells likely to be visited by the mobile user to minimize the handoff processing delay. The likelihood of visiting neighbor cells is estimated using the shadow cluster concept discussed above [71]. Although the virtual admission control is performed in advance, resources are not necessarily reserved in neighbor cells even if the dynamic SLA negotiation gets a positive response. The result of the virtual admission control has to be updated when some event (such as flow termination) takes place prior to the handoff.

The admission control scheme in [147] admits the new session if the number of active sessions in the subnet does not exceed the predefined maximum number of sessions of this particular class (determined offline by the SLA). Handoff requests, on the other hand, are always admitted as long as their required resources are available in the new cell. In order to prioritize handoff calls more efficiently, some resources are left exclusively for handoff sessions, as in the guard band policy (as in [65]). The proposed scheme has been analyzed in a wireless IP network using the DiffServ mechanism. Results show that the proposed scheme reduces the session dropping probability without causing significant degradation to the session blocking probability.

It is shown in [148] that end-to-end QoS guarantee has to be performed at different levels, namely, inter-domain, macro level, and micro level. In the first level, certain measures and mechanisms are used to guarantee QoS when users move from one domain to another. At the macro-level, other measures and mechanisms should be used to guarantee QoS when users move from one subnet to another. Finally, other measures and mechanisms should be used to guarantee QoS when a user moves from one cell to another inside the same subnet. Resource-based admission control has been proposed in [148] for QoS guarantee at the macro-level. The CAC scheme checks the available resources between the gateway home agent (GHA) and gateway foreign agent (GFA), and also the GFA of neighboring cells before admitting the new or handoff calls, and a certain percentage of resources is kept exclusively for handoff calls, as in the guard band policy.

Multihop/ad hoc wireless networks have fundamental distinctions compared with classical wireless networks. Therefore, introducing a novel CAC scheme that takes into consideration the new characteristics is essential for providing

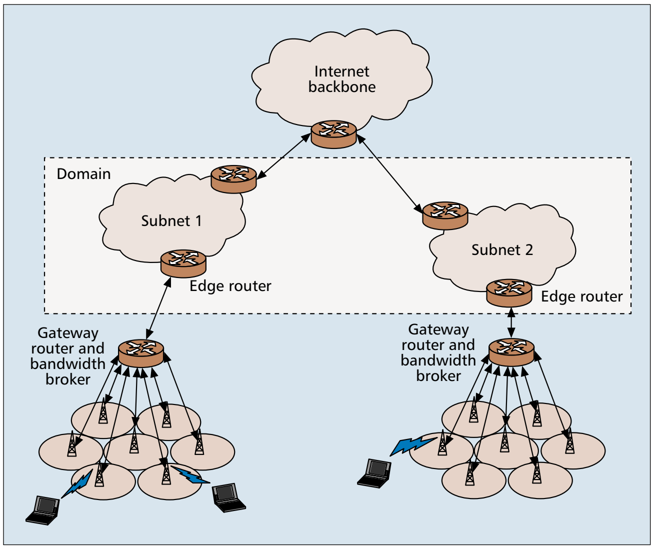


Figure 5. *A simplified architecture of wireless IP networks.*

acceptable QoS in multihop/ad hoc wireless networks. These CAC schemes have to consider the lack of infrastructure (for ad hoc networks), network connectivity, new interference models, traffic routing, decentralized implementation, and power/energy limitations.

A framework for call admission in ad hoc networks has been proposed in [149]. This framework tries to strike a balance between the network connectivity, which is enhanced by admitting more users, and the signal quality in terms of the interference level, which increases by admitting a large number of users. The CAC concept classifies the incoming user as class 1 if (by admitting this user) the number of links will equal one of the critical values; otherwise, the user is classified as class 2. The critical numbers of links, determined by the graph theory, are the ones that increase the connectivity of the existing nodes (users). For instance, when the number of links is equal to $((n/2).\log(n))$ or more, any node can reach other nodes using one or more hops, where n is the number of existing nodes. Class 1 users are admitted if the advantage of increasing the connectivity by admitting those users compensates the degradation in the signal quality due to the potential increase in the interference level, while class 2 users are only admitted if the interference level (after admitting the incoming users) is acceptable. The admission decision is made by an appointed node, which is considered as a virtual cluster head.

In [150] a CAC scheme based on bandwidth availability in multihop network has been proposed. On-demand routing and bandwidth reservation (at included nodes) are employed to explore the possibility of admitting the new (real-time) call. If no routes could be found such that all nodes in that route can be allocated the required resources in terms of the number of time slots, the call is rejected. Time slot reallocation is not considered to alleviate the problem of time-slot matching between neighbor nodes.

A threshold-based CAC for wireless multi-hop voice/data networks using circuit switching has been presented in [151]. Before admitting a call, the number of calls per circuit (connecting a source/destination pair) is checked to determine whether it is less than a threshold value. Also, the sum of the number in each pair of circuits intersecting at any node is checked to ensure that it is less than another threshold value. The threshold values are chosen to minimize the blocking probability using the ordinal optimization techniques.

The CAC scheme proposed in [137] uses adaptive prioritization schemes and resource availability for burst admission in ad hoc wireless networks. For instance, services with lower delay tolerance are admitted first, followed by services with higher delay tolerance, which can be queued until resources become available. Arriving bursts send their requests to the cluster head that manages the resource availability and prioritization scheme. Results show that the proposed scheme outperforms classical non-prioritized burst admission schemes such as first-come-first-serve (FCFS) in terms of P_b.

In [16] a measurement-based CAC has been proposed. When a new call arrives, it first transmits probing packets. The delay incurred by the probing packets is used to determine the service curve, which quantifies the network loading status. The measured service curve is compared by a pre-specified service curve corresponding to the QoS requirements. The CAC scheme accepts the call if the measured service curve is above the universal service curve; otherwise, the call is rejected.

Three CAC schemes for ad hoc wireless LANs have been proposed in [152]. The master device (node) decides whether to admit the arriving call based on the total amount of resources and estimated aggregate link utilization by all existing users. The three schemes differ mainly in the estimation technique of the aggregate link utilization, taking into account the burst nature of the traffic. The first scheme uses the sum of the peak rates of different users as an estimate of the aggregate link utilization. Although this scheme is very simple and can guarantee a low packet loss rate, the conservative estimate leads to a very high blocking rate (up to 50 percent). The second and third schemes use the effective bandwidth technique to estimate the link utilization. The probability of the aggregate link utilization is approximated using the Hoeffding bound [153] and Gaussian distribution in the second and third schemes, respectively. Results show that when a low packet loss rate is required, the Hoeffding bound-based scheme can maximize the aggregate utilization better than the Gaussian distribution-based scheme. On the other hand, the Gaussian distribution-based scheme is more effective in reducing the locking rate if a high packet loss ratio can be tolerated. A similar strategy is used in [154] for mobile ad hoc networks (MANETs). The aggregate link utilization is estimated based on the number of nodes sharing the link and a utilization factor determined empirically (by simulation). However, it should be noted that the utilization factor value is sensitive to many system parameters, and it has to be determined for each particular network configuration.

The popularity of multihop/ad hoc wireless networks is rapidly increasing. Therefore, it is envisioned that CAC schemes will receive more attention in the context of multihop/ad hoc wireless networks since QoS provisioning is more challenging in multihop/ad hoc wireless networks due to their decentralized nature, power/energy constraints, and lack of infrastructure.

It is anticipated that different access technologies will coexist in future wireless networks. Henceforth, beyond 3G wireless networks will encompass 3G wideband CDMA (WCDMA) cellular systems; wireless local area networks (WLAN) such as the IEEE 802.11 family and HIPERLAN; digital video broadcasting (DVB); and broadband wireless access metropolitan area networks (MAN), such as IEEE 802.16. Therefore, RRM in general and CAC in particular have to be revisited to deal with the anticipated new composite radio wireless environment.

Optimal CAC schemes have been studied extensively but separately from other RRM techniques. These optimal CAC schemes, however, do not guarantee optimal overall performance when they are integrated with other RRM techniques such as power control and scheduling. Hence, it is envisaged that optimal integrated RRM techniques (including CAC) are to be adopted in future wireless networks since they can outperform separately optimized RRM techniques.

The dependence of the transmission rate on the achievable SIR in the transmission-rate-based CAC schemes is proposed for future research, particularly when adaptive coding and modulation is employed for efficient resource utilization.

ACKNOWLEDGMENT

The author would like to thank Dr. Halim Yanikomeroglu and Dr. Parsa Larijani for their helpful comments throughout this work.

REFERENCES

[1] J. Zander, "Radio Resource Management in Future Wireless Networks: Requirements and Limitations," *IEEE Commun. Mag.*, Aug. 1997, vol. 35, no. 8, pp. 30–36.

[2] H. Perros and K. Elsayed, "Call Admission Control Schemes: A Review," *IEEE Commun. Mag.*, Nov. 1996, vol. 34, no. 11, pp. 82–91.

[3] J. Choi *et al.*, "Call Admission Control for Multimedia Services in Mobile Cellular Networks: A Markov Decision Approach," *Proc. 5th IEEE Symp. Comp. and Commun. (ISCC 2000)*, 2000, pp. 594–99.

[4] L. Nuaymi, P. Godlewski, and C. Mihailescu, "Call Admission Control Algorithm for Cellular CDMA Systems based on Best Achievable Performance," *Proc. IEEE Vehic. Tech. Conf. (VT'00-Spring)*, Tokyo, 2000, vol. 1, pp. 375–79.

[5] C. Huang and R. Yates, "Call Admission in Power Controlled CDMA Systems," *Proc. IEEE 46th Vehic. Tech. Conf. (VTC'96)*, 1996, vol.3, pp. 1665–69.

[6] D. Zhao, X. Shen, and J. Mark, "Call Admission Control for Heterogeneous Services in Wireless Networks Communications," *Proc. IEEE Int'l. Conf. Commun. (ICC'00)*, 2000, vol. 2, pp. 964–68.

[7] M. Naghshineh and A. Acampora, "QOS Provisioning in Microcellular Networks Supporting Multimedia Traffic," *Proc. 14th Annual Joint Conf. IEEE Comp. and Commun. Societies (INFOCOM '95)*, 1995, vol. 3, pp. 1075–84.

[8] M. Naghshineh and M. Schwartz, "Distributed Call Admission Control in Mobile/Wireless Networks Personal, Indoor and Mobile Radio Communications," *Proc. 6th IEEE Int'l. Symp. Pers., Indoor and Mobile Radio Commun. (PIMRC'95)*, 1995, vol. 1, pp. 289–93.

[9] Z. Liu and M. El Zarki, "SIR-based Call Admission Control for DS-CDMA Cellular Systems," *IEEE JSAC*, vol.12, no. 4, May 1994, pp. 638–44.

[10] B. Epstein and M. Schwartz, "Predictive QoS-based Admission Control for Multiclass Traffic in Cellular Wireless Networks," *IEEE JSAC*, vol. 18, no. 3, Mar. 2000, pp. 523–34.

[11] S. Kim, T. Kwon, and Y. Choi, "Call Admission Control for Prioritized Adaptive Multimedia Services in Wireless/Mobile Networks," *Proc. IEEE Vehic. Tech. Conf. (VTC '00-Spring)*, Tokyo, 2000, vol. 2, pp. 1536–40.

[12] R. Ramjee, R. Nagarajan, and D. Towsley, "On Optimal Call Admission Control in Cellular Networks," *Proc. 15th Annual Joint Conf. IEEE Comp. and Commun. Societies (INFOCOM '96)*, 1996, vol. 1, pp. 43–50.

[13] R. Ramjee, R. Nagarajan, and D. Towsley, "On Optimal Call Admission Control in Cellular Networks," *Wireless Networks*, 1997, pp. 29–41.

[14] M. Han and A. Nilsson, "Population-based Call Admission Control in Wireless Cellular Networks Communications," *Proc. IEEE Int'l. Conf. Commun. (ICC'00)*, 2000, vol. 3, pp. 1519–23.

[15] Z. Dziong, M. Jia, and P. Mermelstein, "Adaptive Traffic Admission for Integrated Services in CDMA Wireless-access Networks," *IEEE JSAC*, vol. 14, no. 9, Dec. 1996, pp. 1737–47.

[16] S. Valaee and B. Li, "Distributed Call Admission Control for Ad Hoc Networks," *Proc. IEEE Vehic. Tech. Conf. (VTC'02-Fall)*, 2002, vol. 2, pp. 1244–48.

[17] R. Jain and E. Knightly, "A Framework for Design and Evaluation of Admission Control Algorithms in Multi-service Mobile Networks," *Proc. 18th Annual Joint Conf. IEEE Comp. and Commun. Societies (INFOCOM '99)*, 1999, vol. 3, pp. 1027–35.

[18] C. Chao and W. Chen, "Connection Admission Control for Mobile Multiple-class Personal Communications Networks," *IEEE JSAC*, vol. 15, no. 8 , Oct. 1997, pp. 1618–26.

[19] J. Knutsson *et al.*, "Downlink Admission Control Strategies for CDMA Systems in a Manhattan Environment," *Proc. IEEE Vehic. Tech. Conf. (VTC '98)*, pp. 1453–57.

[20] M. Missiroli, R. Patelli, and L. Vignali, "Admission Control for Mixed Services in Downlink WCDMA in Different Propagation Environments," *Proc. 12th IEEE Int'l. Symp. Pers., Indoor and Mobile Radio Commun. (PIMRC'01)*, 2001, vol. 2, pp. E-32–E-37.

[21] W. Jeon and D. Jeong, "Call Admission Control for Mobile Multimedia Communications with Traffic Asymmetry between Uplink and Downlink," *IEEE Trans. Vehic. Tech.*, vol. 50, no. 1, Jan. 2001, pp. 59–66.

[22] Y. Ishikawa and N. Umeda, "Capacity Design and Performance of Call Admission Control in Cellular CDMA Systems," *IEEE JSAC*, vol. 15, no. 8, Oct. 1997, pp.1627–35.

[23] Y. Guo and B. Aazhong, "Call Admission Control in Multiclass Traffic CDMA Cellular System Using Multiuser Antenna Array Receiver," *Proc. IEEE Vehic. Tech. Conf. (VTC '00-Spring)*, May 2000, vol. 1, pp. 365–69.

[24] J. Evans and D. Everitt, "Effective Bandwidth-based Admission Control for Multiservice CDMA Cellular Networks," *IEEE Trans. Vehic. Tech.*, vol. 48, no. 1, Jan. 1999, pp. 36–46.

[25] M. Andersin, Z. Rosberg, and J. Zander, "Soft and Safe Admission Control in Cellular Networks," *IEEE Trans. Net.*, vol. 5, no. 2, Apr. 1997, pp. 255–65.

[26] J. Kuri and P. Mermelstein, "Call Admission on the Uplink of a CDMA System Based on Total Received Power Communications," *Proc. IEEE Int'l. Conf. Commun. (ICC '99)*, 1999, vol. 3, pp. 1431–36.

[27] W. Yang and E. Geraniotis, "Admission Policies for Integrated Voice and Data Traffic in CDMA Packet Radio Networks," *IEEE JSAC*, vol. 12, no. 4, May 1994, pp. 654–64.

[28] I. Kim, B. Shin, and D. Lee, "SIR-based Call Admission Control by Intercell Interference Prediction for DS-CDMA Systems," *IEEE Commun. Letters*, vol. 4, no. 1, Jan. 2000, pp. 29–31.

[29] D. Kim, "On Upper Bounds of SIR-based Call Admission Threshold in Power-controlled DS-CDMA Mobile Systems," *IEEE Commun. Letters*, vol. 6, no. 1, Jan. 2002, pp. 13–15.

[30] Y. Chen, C. Chang, and S. Shen, "An Outage-based Fuzzy Call Admission Control for WCDMA," *Proc. 12th IEEE Int'l. Symp. Pers., Indoor and Mobile Radio Commun. (PIMRC'01)*, 2001, vol. 1, pp. B-15–B-19.

[31] C. Chuah, R. Yates, and D. Goodman, "Integrated Dynamic Radio Resource Management," *Proc. IEEE Vehic. Tech. Conf. (VTC '95)*, 1995, vol. 2, pp. 584–88.

[32] J. Chak and W. Zhuang, "Connection Admission Control for Indoor Multimedia Wireless Communications," *Proc. IEEE Vehic. Tech. Conf. (VTC '98)*, 1998, pp. 2570–74.

[33] C. Carciofi, M. Frullone, and M. Missiroli, "Third Generation W-CDMA in Real Environments: Impact of Quality Adaptive Call Admission Policies on the Spatial Distribution of Blocking Probability," *Proc. ACTS'99*.

[34] M. Casoni, G. Immovilli, and M. Merani, "Admission Control in T/CDMA Systems Supporting Voice and Data Applications," *IEEE Trans. Wireless Commun.*, vol. 1, no. 3 , July 2002, pp. 540–48.

[35] D. Ayyagari and A. Ephremides, "Optimal Admission Control in Cellular DS-CDMA Systems with Multimedia Traffic," *IEEE Trans. Wireless Commun.*, vol. 2, no. 1, Jan. 2003, pp. 195–202.

[36] T. Shu and Z. Niu, "Call Admission Control using Differentiated Outage Probabilities in Multimedia DS-CDMA Networks with Imperfect Power Control," *Proc. 11th Int'l. Conf. Comp. Commun. and Net.*, 2002, Oct. 2002, pp. 336–41.

[37] J. Chang, J. Chung, and D. Sung, "Admission Control Schemes for Soft Handoff in DS-CDMA Cellular Systems Supporting Voice and Stream-type Data Services," *IEEE Trans. Vehic. Tech.*, vol. 51, no. 6, Nov. 2002, pp. 1445–59.

[38] C. Ho *et al.*, "On Call Admission Control in DS/CDMA Cellular Networks," *IEEE Trans. Vehic. Tech.*, vol. 50, no. 6, Nov. 2001, pp. 1328–43.

[39] T. Liu and J. Silvester, "Joint Admission/Congestion Control for Wireless CDMA Systems Supporting Integrated Services," *IEEE JSAC*, vol. 16, no. 6, Aug. 1998, pp. 845–57.

[40] J. Wu, "Performance Analysis of QoS-Based Voice/Data CDMA Systems," *Wireless Pers. Commun.*, June 2000, pp. 223–36.

[41] Y. Ma, J. Han, and K. Trivedi, "Call Admission Control for Reducing Dropped Calls in Code Division Multiple Access (CDMA) Cellular Systems," *Proc. 9th Annual Joint Conf. IEEE Comp. and Commun. Societies (INFOCOM '00)*, vol. 3, pp. 1481–90.

[42] P. Larijani, R. Hafez, and I. Lambadaris, "Adaptive Access Control for Multimedia Traffic in a CDMA Cell with Imperfect Power Control," *Proc. 9th IEEE Int'l. Symp. Pers., Indoor and Mobile Radio Commun. (PIMRC '97)*, 1997, pp. 729–33.

[43] P. Larijani, R. Hafez, and I. Lambadaris, "Two-Level Access Control Strategy for Multimedia CDMA," *Proc. IEEE Int'l. Conf. Commun. (ICC '98)*, 1998, pp. 82–87.

[44] J. Evans and D. Everitt, "Call Admission Control in Multiple Service DS-CDMA Cellular Networks," *Proc. IEEE Vehic. Tech. Conf. (VTC '96)*, 1996, vol. 1, pp. 227–31.

[45] J. Zander, "Performance of Optimum Transmitter Power Control in Cellular Radio Systems," *Proc. IEEE Trans. Vehic. Tech.*, vol. 41, no. 1, Feb. 1992, pp. 57–62.

[46] D. Kim, "Efficient Interactive Call Admission Control in Power-controlled Mobile Systems," *IEEE Trans. Vehic. Tech.*, vol. 49, no. 3, May 2000, pp. 1017–28.

[47] N. Bambos, S. Chen, and G. Pottie, "Radio Link Admission Algorithms for Wireless Networks with Power Control and Active Link Quality Protection," *Proc. IEEE 14th Annual Joint Conf. IEEE Comp. and Commun. Societies (INFOCOM '95)*, 1995, vol. 1, pp. 97–104.

[48] J. Knutsson *et al.*, "Evaluation of Admission Control for CDMA Systems in a Manhattan Environment," *Proc. CDMA Int'l. Conf. (CIC '97)*, 1997.

[49] M. Park and S. Oh, "Dynamic Power and Resource Allocation for Wireless Multimedia Traffics in Reverse Link of WCDMA Systems," *Proc. Wireless '99*, 1999, pp. 85–91.

[50] F. Chiti *et al.*, "Dynamic SIR-based Admission Control Algorithm for 3G Wireless Networks," *Proc. IEEE Int'l. Conf. Commun. (ICC '03)*, vol. 3, May 2003, pp. 1907–11.

[51] K. Pedersen and P. Mogensen, "Directional Power-based Admission Control for WCDMA Systems using Beamforming Antenna Array Systems," *IEEE Trans. Vehic. Tech.*, vol. 51, no. 6, Nov. 2002, pp. 1294–303.

[52] K. Kim and Y. Han, "A Call Admission Control with Thresholds for Multi-rate Traffic in CDMA Systems," *Proc. IEEE Vehic. Tech. Conf. (VT'00-Spring)*, Tokyo, May 2000, vol. 2, pp. 830–34.

[53] A. Raha *et al.*, "Admission Control for Hard Real-time Connections in ATM LANs," *IEE Proc. Commun.*, vol. 148, no. 4, Aug. 2001, pp. 217–28.

[54] C. Ho, C. Lea, and G. Stuber, "Call Admission Control in the Microcell/Macrocell Overlaying System," *IEEE Trans. Vehic. Tech.*, vol. 50, no. 4 , July 2001, pp. 992–1003.

[55] C. Ho *et al.*, "Impact of the Cell Size on the Cell's Erlang Capacity and Call Admission Control in the DS/CDMA Cellular Networks," *Proc. IEEE Vehic. Tech. Conf. (VT'00-Spring)*, Tokyo, May 2000, vol. 1, pp. 385–89.

[56] C. Ho, C. Lea, and G. Stuber, "Call Admission Control in Hierarchical Cellular Networks," *Proc. IEEE Vehic. Tech. Conf. (VTC '99)*, 1999, vol. 1, pp. 320–24.

[57] S. Singh, V. Krishnamurthy, and H. Poor, "Integrated Voice/Data Call Admission Control for Wireless DS-CDMA Systems," *IEEE Trans. Sig. Proc.*, vol. 50, no. 6, June 2002, pp. 1483–1495.

[58] R. Akl *et al.*, "Call Admission Control Scheme for Arbitrary Traffic Distribution in CDMA Cellular Systems," *Proc. IEEE WCNC 2000*, vol. 1, Sept. 2000, pp. 465–70.

[59] S. Akhtar, S. Malik, and D. Zeghlache, "Prioritized Admission Control for Mixed Services in UMTS WCDMA Networks," *Proc. 12th IEEE Int'l. Symp. Pers., Indoor and Mobile Radio Commun. (PIMRC'01)*, vol. 1, Oct. 2001, pp. B-133–B-137.

[60] M. Haleem, D. Avidor, and R. Valenzuela, "Fixed Wireless Access System with Autonomous Resource Assignment," *Proc. 9th IEEE Int'l. Symp. Personal, Indoor and Mobile Radio Commun. (PIMRC '98)*, 1998, vol. 3, pp. 1438–42.

[61] P. Beming and M. Frodigh, "Admission Control in Frequency Hopping GSM Systems," *Proc. IEEE Vehic. Tech. Conf. (VTC '97)*, 1997, pp. 1282–286.

[62] A. Arregui and J. Dunlop, "Distributed Call Admission Control in Partially Loaded TDMA Systems," *Proc. IEEE Vehic. Tech. Conf. (VTC '98)*, 1998, vol. 2, pp. 1361–65.

[63] A. Arregui and J. Dunlop, "Benefits and Feasibility of the Partial Loading Approach in Cellular Mobile Radio Systems," *IEEE Trans. Vehic. Tech.*, vol. 49, no. 4, July 2000, pp. 1049–64.

[64] M. Ahmed and S. Mahmoud, "Soft Capacity Analysis of TDMA Systems with Frequency Hopping and Smart Antennas," *IEEE Trans. Vehic. Tech.*, July 2002, vol. 51, no. 4, pp. 636–47.

[65] D. Hong and S. Rappaport, "Traffic Model and Performance Analysis for Cellular Mobile Radio Telephone Systems with Prioritized and Nonprioritized Handoff Procedures," *IEEE Trans. Vehic. Tech.*, vol. 35, no. 3, Aug. 1986, pp. 77–92.

[66] M. Naghshineh and A. Acampora, "Design and Control of Micro-cellular Networks with QOS Provisioning for Real-time Traffic," *Proc. 3rd IEEE Int'l. Conf. Universal Personal Commun. (ICUPC '94)*, 1994, pp. 376–81.

[67] M. Naghshineh and A. Acampora, "Design and Control of Micro-cellular Networks with QOS Provisioning for Data Traffic," *Wireless Networks*, vol. 3, no. 4, 1997, pp. 249–56.

[68] A. Acampora and M. Naghshineh, "An Architecture and Methodology for Mobile-Executed Handoff in Cellular ATM Networks," *IEEE JSAC*, vol. 12, no. 8 , Oct. 1994, pp. 1365–75.

[69] A. Acampora and M. Naghshineh, "Control and Quality of Service Provisioning in High-Speed Microcellular Networks," *IEEE Pers. Commun. Mag.*, 2nd Quarter, 1994, pp. 36–43.

[70] C. Oliviera, J. Kim, and T. Suda, "An Adaptive Bandwidth Reservation Scheme for High-Speed Multimedia Wireless NetWorks," *IEEE JSAC*, vol. 16, no. 6, Aug. 1998, pp. 858–72.

[71] D. Levine, I. Akyildiz, and M. Naghshineh, "The Shadow Cluster Concept for Resource Allocation and Call Admission in ATM-based Wireless Networks," *Proc. 1st Int'l. Conf. Mobile Comp. and Net. (MOBICOM '95)*, 1995, pp. 142–50.

[72] D. Levine, I. Akyildiz, and M. Naghshineh, "A Resource Estimation and Call Admission Algorithm for Wireless Multimedia Networks using the Shadow Cluster Concept," *IEEE/ACM Trans. Net.*, vol. 5, no. 1, Feb. 1997, pp. 1–12.

[73] R. Raad, E. Dutkiewicz, and J. Chicharo, "Connection Admission Control in Micro-cellular Multi-service Mobile Networks," *Proc. 5th IEEE Symp. Computers and Commun. (ISCC '00)*, 2000, pp. 600–06.

[74] O. Yu and V. Leung, "Adaptive Resource Allocation for Prioritized Call Admission over an ATM-based Wireless PCN," *IEEE JSAC*, vol. 15, no. 7, Sept. 1997, pp. 1208–25.

[75] N. Bartolini and I. Chlamtac, "Improving Call Admission Control Procedures by using Handoff Rate Information," *Wiley Wireless Commun. and Mobile Comp. J.*, 2001, pp. 257–68.

[76] Y. Fang, "Thinning Schemes for Call Admission Control in Wireless Networks," *IEEE Trans. Comp.*, vol. 52, no. 5, May 2003, pp. 685–87.

[77] Y. Fang and Yi Zhang, "Call Admission Control Schemes and Performance Analysis in Wireless Mobile Networks," *IEEE Trans. Vehic. Tech.*, vol. 51, no. 2, Mar. 2002, pp. 371–82.

[78] J. Hou and Y. Fang, "Mobility-based Call Admission Control Schemes for Wireless Mobile Networks," *Wireless Commun. and Mobile Comp.*, Jan. 2001, pp. 269–82.

[79] S. Nelakuditi *et al.*, "Revenue-based Call Admission Control for Wireless Cellular Networks," *Proc. IEEE Int'l. Conf. Pers. Wireless Commun.*, 1999, pp. 486–90.

[80] S. Cho *et al.*, "QoS-Oriented Bandwidth Management Scheme for Stable Multimedia Services on the IMT-2000 Networks," *Proc. Int'l. Conf. Info. Tech.: Coding and Computing*, 2000, pp. 289–94.

[81] M. El-kadi, S. Olariu, and H. Abdel-Wahab, "A Rate-based Borrowing Scheme for QoS Provisioning in Multimedia Wireless Networks," *IEEE Trans. Parallel and Distributed Systems*, vol. 13, no. 2, Feb. 2002, pp. 156– 66.

[82] H. Lin and S. Tzeng, "Double-Threshold Admission Control in Cluster-based Micro/Picocellular Wireless Networks," *Proc. IEEE Vehic. Tech. Conf. (VTC '00-Spring)*, Tokyo, May 2000, vol. 2, pp. 1440–44.

[83] J. Peha and A. Sutivong, "Admission Control Algorithms for Cellular Systems," *ACM/Baltzer Wireless Networks*, Mar. 2001, vol. 7, no. 2, pp. 117–25.

[84] A. Sutivong and J. Peha, "Performance Comparison of Call Admission Control Algorithms in Cellular Systems," *Proc. IEEE Global Telecommunications Conf. (GLOBECOM '97)*, 1997, vol. 3, pp. 1645–49.

[85] A. Sutivong and J. Peha, "Novel Heuristics for Call Admission Control in Cellular Systems," *Proc. IEEE 6th Int'l. Conf. Universal Personal Commun. (ICUPC '97)*, 1997, vol. 1, pp. 129–33.

[86] M. Naghshineh and M. Schwartz, "Distributed Call Admission Control in Mobile/Wireless Networks," *IEEE JSAC*, vol. 14, no. 4, May 1996, pp. 711–17.

[87] O. Koyuncu, S. Das, and H. Ernam, "Dynamic Resource Assignment using Network Flows in Wireless Data Networks," *Proc. IEEE Vehic. Tech. Conf. (VTC '99)*, 1999, vol. 1, pp. 1–5.

[88] Q. Gao and A. Acampora, "Performance Comparison of Admission Control Strategies for Future Wireless Networks," *Proc. IEEE Wireless Commun. and Net. Conf., WCNC2002*, vol. 1, Mar. 2002, pp. 317–21.

[89] S. Das *et al.*, "A Call Admission and Control Scheme for Quality-of-service (QoS) Provisioning in Next Generation Wireless Networks," *Wireless Networks*, vol. 6, no. 1, 2000, pp. 17–30.

[90] S. Das, S. Sen, and R. Jayaram, "Call Admission and Control for Quality-of-service Provisioning in Cellular Networks," *Proc. 6th IEEE Int'l. Conf. Universal Personal Commun. (ICUPC '97)*, 1997, vol. 1, pp. 109–13.

[91] J. Kim, E. Jeong, and J. Cho, "Call Admission Control for Non-uniform Traffic in Wireless Networks," *IEEE Electronics Letters*, vol. 36, no. 1, Jan. 2000, pp. 96–97.

[92] A. Aljadhai and T. Znati, "A Framework for Call Admission Control and QoS Support in Wireless Environments," *Proc. 18th Annual Joint Conf. IEEE Comp. and Commun. Societies (INFOCOM '99)*, 1999, vol. 3, pp. 1019–26.

[93] A. Aljadhai and T. Znati, "A Predictive Adaptive Scheme to Support QoS Guarantees in Multimedia Wireless Networks," *Proc. IEEE Int'l. Conf. Commun. (ICC '99)*, 1999, vol. 1, pp. 221–25.

[94] V. Phan-Van, "Soft Decision Call Admission Control Versus Static Fixed Channel Assignment and Interference Measurement-based Policies for WCDMA Cellular PCNs" *Proc. 12th IEEE Int'l. Symp. Pers., Indoor and Mobile Radio Commun. (PIMRC'01)*, 2001, vol. 2, pp. E-27–E-31.

[95] J. Lee and S. Bahk, "Simple Admission Control Schemes Supporting QoS in Wireless Multimedia Networks," *Electronics Letters*, vol. 37 no. 1, May 2001, pp. 712–13.

[96] S. Choi and K. Shin, "Comparison of Connection Admission-control in the Presence of Hand-offs in Cellular Networks," *Proc. 4th Int'l. Conf. Mobile Comp. and Net. (MOBICOM '98)*, 1998, pp. 264–75.

[97] J. Qiu and J. Mark, "Service Scheduling and CAC for QoS Guarantee in Future PCS," *Proc. IEEE Global Telecommun. Conf. (GLOBECOM '98)*, 1998, vol. 4, pp. 2039–44.

[98] D. Zhao, X. Shen, and J. Mark, "Efficient Call Admission Control for Heterogeneous Services in Wireless Mobile ATM Networks," *IEEE Commun. Mag.*, vol. 38, no. 10, Oct. 2000, pp. 72–78.

[99] F. Davoli, P. Maryni, and C. Nobile, "A Call Admission Control Strategy for Multiservice Wireless Cellular Packet Networks," *Int'l. J. Wireless Info. Net.*, vol. 3, no. 4, Oct. 1996, pp. 235–242.

[100] A. Iera, S. Marano, and A. Molinaro, "Transport and Control Issues in Multimedia Wireless Networks," *Wireless Networks*, vol. 2, no. 3, 1996, pp. 249–61.

[101] K. Begain, G. Bolch, and M. Telek, "Scalable Schemes for Call Admission and Handover in Cellular Networks with Multiple Services," *Wireless Pers. Commun.*, Nov. 2000, pp. 125–44.

[102] B. Subramaniam and C. Murthy, "Application Semantics and Seamlessness-based Admission Control Policy for Multimedia Mobile Networks," *Multimedia Tools and Applications*, vol. 9, no. 1, July 1999, pp. 7–28.

[103] D. Reininger and R. Izmailov, "Admission and Bandwidth Allocation for Soft-QoS Guarantees in Mobile Multimedia Networks," *Proc. IEEE Wireless Communications and Networking Conf. (WCNC '99)*, 1999, vol. 3, pp. 1513–1517.

[104] T. Kwon and Y. Choi, "Call Admission Control in Mobile Cellular Network Based on Macroscopic Modeling of Vehicular Traffic," *Proc. IEEE Vehic. Tech. Conf. (VTC '98)*, 1998, vol. 3, pp. 1940–44.

[105] V. Bharadwaj and A. Karandikar, "Hidden Markov Model-based Resource Estimation and Call Admissions in Mobile Cellular Networks," *Proc. Int'l. Conf. Personal Wireless Commun. (ICPWCC '99)*, 1999, pp. 321–25.

[106] L. Garcia, *Probability and Random Process for Electrical Engineers*, Addison-Wesley, 1994 (Prentice-Hall).

[107] O. Baldo and A. Aghvami, "On-line Distributed Connection Admission Control for Wireless ATM Telecommunications," *IEE Conf. Telecommun. (ICT '98)*, 1998, pp. 72–75.

[108] O. Baldo, L. Thong, and A. Aghvami, "Performance of Distributed Call Admission Control for Multimedia High-Speed Wireless/Mobile ATM networks Communications," *Proc. IEEE Int'l. Conf. Commun. (ICC '99)*, 1999, vol. 3, pp. 1982–86.

[109] O. Baldo and A. Aghvami, "Base-Station Supported Call Admission Control for Wireless ATM," *Proc. Int'l. Conf. Universal Personal Commun. (ICUPC '98)*, 1998, vol. 1, pp. 477–81.

[110] O. Baldo and A. Aghvami, "Decentralized Call Admission Control for Wireless ATM," *IEE Proc. Commun.*, vol. 146, no. 6, Dec. 1999, pp. 366–71.

[111] S. Wu, K. Wong, and B. Li, "A Dynamic Call Admission Policy with Precision QoS Guarantee using Stochastic Control for Mobile Wireless Networks," *IEEE/ACM Trans. Net.*, vol. 10, no. 2, Apr. 2002, pp. 257–71.

[112] Y. Iraqi and R. Boutaba, "When is it Worth Involving Several Cells in the Call Admission Control Process for Multimedia Cellular Networks?" *Proc. IEEE Int'l. Conf. Commun. (ICC'01)*, vol. 2, June 2001, pp. 336–40.

[113] J. Lee *et al.*, "Realistic Cell-Oriented Adaptive Admission Control for QoS Support in Wireless Multimedia Networks," *IEEE Trans. Vehic. Tech.*, vol. 52, no. 3, May 2003, pp. 512–24.

[114] J. Misic and T. Bun, "Adaptive Admission Control in Wireless Multimedia Networks under Non-Uniform Traffic Conditions," *IEEE JSAC*, vol. 18, no. 11, Nov. 2000, pp. 2429–42.

[115] H. Oh and S. Seo, "A New Call Admission Control Algorithm for Multi-Class Services in Wireless ATM," *Proc. IEEE 50th Vehic. Tech. Conf. (VTC '99-Fall)*, 1999, vol. 3, pp. 1740–44.

[116] W. Ming, J. Misic, and S. Chanson, "Call Admission Control in DCA Wireless Network," *Proc. 9th IEEE Int'l. Symp. Personal, Indoor and Mobile Radio Commun. (PIMRC '98)*, 1998, vol. 2, pp. 665–71.

[117] J. Misic, S. Chanson, and F. Lai, "Event-based Resource Estimation in Admission Control for Wireless Networks with Heterogeneous Traffic," *Mobile Comp. and Commun. Review*, vol. 1, no.4, Oct. 1997, pp. 17–24.

[118] D. Eom *et al.*, "Call Admission Control for QoS Provisioning in Multimedia Wireless ATM Networks," *Institute of Electronics, Info. & Commun. Eng. (IEICE) Trans. Commun.*, vol. E82-B, no. 1, Jan. 1999, pp. 14–23.

[119] T. Kwon *et al.*, "Threshold-type Call Admission Control in Wireless/Mobile Multimedia Networks using Prioritized Adaptive Framework," *IEEE Electronics Letters*, vol. 36, no. 9, Apr. 2000, pp. 852–54.

[120] C. Ho and C. Lea, "Finding Better Call Admission Policies in Wireless Networks," *Proc. IEEE Vehic. Tech. Conf. (VTC '98)*, 1998, vol. 3, pp. 2135–39.

[121] M. Saquib and R. Yates, "Optimal Call Admission to a Mobile Cellular Network," *Proc. IEEE Vehic. Tech. Conf. (VTC 95)*, 1995, vol. 1, pp. 190–94.
[122] C. Ho and C. Lea, "Improving Call Admission Policies in Wireless Networks," *Wireless Networks*, vol. 5, no. 4, pp. 257–65.
[123] Y. Xiao, C. Chen, and Y. Wang, "Quality of Service Provisioning Framework for Multimedia Traffic in Wireless/Mobile Networks," *Proc. 9th Int'l. Conf. Comp. Commun. and Net. (ICCN 2000)*, 2000, pp. 644–48.
[124] A. Yener and C. Rose, "Genetic Algorithms Applied to Cellular Call Admission: Local Policies," *IEEE Trans. Vehic. Tech.*, vol. 46, no. 1, Feb. 1997, pp. 72–79.
[125] Y. Xiao, C. Chen, and Y. Wang, "A Near Optimal Call Admission Control with Genetic Algorithm for Multimedia Services in Wireless/Mobile Networks," *Proc. IEEE National Aerospace and Electronics Conf. (NAECON 2000)*, 2000, pp. 787–92.
[126] X. Tian and C. Ji, "Bounding the Performance of Dynamic Channel Allocation with QoS Provisioning for Distributed Admission Control in Wireless Networks," *IEEE Trans. Vehic. Tech.*, vol. 50, no. 2, Mar. 2001, pp. 388–97.
[127] J. Jiang and T. Lai," Call Admission Control vs. Bandwidth Reservation: Reducing Handoff Call Dropping Rate and Providing Bandwidth Efficiency in Mobile Networks," *Proc. Int'l. Conf. Parallel Proc.*, 2000, pp. 581–88.
[128] T. Kwon *et al.*, "Measurement-based Call Admission Control for Adaptive Multimedia in Wireless/Mobile Networks," *Proc. IEEE Wireless Commun. and Net. Conf. (WCNC '99)*, 1999, vol. 2, pp. 540–44.
[129] A. Valko and A. Campbell, "An Efficiency Limit of Cellular Mobile Systems," *Comp. Commun.*, vol. 23, no. 5-6, Mar. 2000, pp. 441-451.
[130] J. Capone and I. Stavrakakis, "Determining the Call Admission Region for Real-time Heterogeneous Applications in Wireless TDMA Networks," *IEEE Trans. Net.*, vol. 12, no. 2, Mar.–Apr. 1998, pp. 38–47.
[131] P. Koutsakis, M. Paterakis, and S. Psychis, "Call Admission Control and Traffic Policing Mechanisms for the Wireless Transmission of Layered Videoconference Traffic from MPEG-4 and H.263 Video Coders," *Proc. 13th IEEE Int'l. Symp. Pers., Indoor and Mobile Radio Commun. (PIMRC'02)*, vol. 5, Sept. 2002, pp. 2155–59.
[132] V. Kumar and P. Venkataram, "A LP-RR Principle-based Admission Control for a Mobile Network Systems," *IEEE Trans. Man and Cybernetics, Part C*, vol. 32, no. 4, Nov. 2002, pp. 293–306.
[133] Y. Xiao, C. Chen, and Y. Wang, "Quality of Service and Call Admission Control for Adaptive Multimedia Services in Wireless/Mobile Networks," *Proc. IEEE National Aerospace and Electronics Conf. (NAECON '2000)*, 2000, pp. 214–20.
[134] C. Comaniciu *et al.*, "QoS Guarantees for Third Generation (3G) CDMA Systems via Admission and Flow Control," *Proc. IEEE Vehic. Tech. Conf. (VT'00-Fall)*, 2000, vol. 1, pp. 249–56.
[135] T. Kwon and M. Naghshineh, "Optimal Distributed Call Admission Control for Multimedia Services in Mobile Cellular Network," *Proc. Mobile Multimedia (MoMu '98)*, 1998.
[136] W. Ibrahim, J. Chinnek, and S. Periyalwar, "A QoS-based Charging and Resource Allocation Framework for Next Generation Wireless Networks," *Wireless Commun. and Mobile Comp.*, Nov. 2003.
[137] D. Ayyagari and A. Ephremides, "Admission Control with Priorities: Approaches for Multi-rate Wireless Systems," *Mobile Networks and Applications*, vol. 4, 1999, pp. 209–18.
[138] J. Hou, J. Yang, and S. Papavassiliou, "Integration of Pricing with Call Admission Control to Meet QoS Requirements in Cellular Networks," *IEEE Trans. Parallel and Distributed Systems*, vol. 13, no. 9, Sept. 2002, pp. 898–910.
[139] M. Ahmed and S. Mahmoud, "QoS-based Admission Control Algorithm for Integrated Services Voice/Data in Wideband DS-CDMA with Switched-Beam Antennas," *Wireless Pers. Commun.*, vol. 6, no. 1, Jan. 2003, pp. 11–29.
[140] Y. Haung and J. Ho, "Distributed Call Admission Control for a Heterogeneous PCS Network Computer," *IEEE Trans. Comp.*, vol. 51, no. 12 , Dec. 2002, pp. 1400–09.
[141] A. Ween *et al.*, "Dynamic Resource Allocation for Multi-service Packet-based LEO Satellite Communications," *Proc. IEEE Global Telecommun. Conf. (GLOBECOM '98)*, 1998, vol. 5, pp. 2954–59.
[142] S. Chung and J. Lee, "Call Admission Control in Cellular Multiservice Networks using Virtual Partitioning with Priority Networks," *Proc. IEEE Int'l. Conf. Net. (ICON 2000)*, 2000, pp. 8–12.
[143] L. Badia, M. Zorzi, and A. Gazzini, "On the Impact of User Mobility on Call Admission Control in WCDMA Systems," *Proc. IEEE Vehic. Tech. Conf. (VTC '02-Fall)*, vol. 1, Sept. 2002, pp. 121–26.
[144] T. Janevski, *Traffic Analysis and Design of Wireless IP Networks*, Artech House, 2003.
[145] J. Kim and A. Jamalipour, "Traffic Management and QoS Provisioning in Future Wireless IP Networks," *IEEE Pers. Commun. Mag.*, vol. 8, no. 5, Oct. 2001, pp. 46– 55.
[146] O. Akan and B. Baykal, "Dynamic SLA Management in Cellular DiffServ Networks," *Proc. Int'l. Conf. Telecommunications (ICT'03)*, 23 Feb.–1 Mar. 2003, pp. 330–33.
[147] Y. Cheng and W. Zhuang, "DiffServ Resource Allocation for Fast Handoff in Wireless Mobile Internet," *IEEE Commun. Mag.*, vol. 40, no. 5, May 2002, pp. 130–36.
[148] K. Kim and S. Kim, "Hierarchical Admission Control Scheme for Supporting Mobility in Mobile IP," *Proc. 8th Int'l. Conf. Mobile Computing and Net. (MOBICOM '02)*, vol. 1, Oct. 2002, pp. 431–35.
[149] M. Chiang and G. Carlsson, "Admission Control, Power Control and QoS Analyses for Ad Hoc Wireless Networks," *Proc. IEEE Int'l. Conf. Commun. (ICC '01)*, 2001, vol. 1, pp. 245–49.
[150] C. Lin, "Admission Control in Time-slotted Multihop Mobile Networks," *IEEE JSAC*, vol. 19, no. 10, Oct. 2001, pp. 1974–83.
[151] J. Wieselthier, C. Barnhart, and A. Ephremides, "Ordinal Optimization of Admission Control in Wireless Multihop Voice/Data Networks via Standard Clock Simulation," *Proc. 13th Annual Joint Conf. IEEE Comp. and Commun. Societies (INFOCOM '94)*, 1994, vol. 1, pp. 29–38.
[152] G. Razzano and A. Curcio, "Performance Comparison of Three Call Admission Control Algorithms in a Wireless Ad Hoc Network," *Proc. Int'l. Conf. Commun. Tech. (ICCT'03)*, vol. 2, Apr. 2003, pp. 1332–36.
[153] W. Hoeffding, "Probability Inequalities for Sums of Bounded Random Variables," *American Statistical Association Journal*, vol. 58, Mar. 1963, pp. 13–30.
[154] Y. Dong, D. Makrakis, and T. Sullivan, "Effective Admission Control in Multihop Mobile Ad Hoc Networks," *Proc. Int'l. Conf. Commun. Tech. Proc. (ICCT'03)*, vol. 2, Apr. 2003, pp. 1291–94.

BIOGRAPHY

MOHAMED HOSSAM AHMED (mhahmed@engr.mun.ca) received B.Sc. and M.Sc. degrees in electronics and communications engineering from Ain Shams University, Cairo, Egypt in 1990 and 1994, respectively. He received a Ph.D. degree in electrical engineering in 2001 from Carleton University, Ottawa, Canada. From 2001 to 2003 he worked as a senior research associate in the department of systems and computer engineering at Carleton University. In April 2003 he joined the faculty of engineering and applied science, Memorial University of Newfoundland, as an assistant professor of electrical and computer engineering. He has served as a technical program committee member of various conferences and as a guest editor for the *Wiley Journal on Wireless Communications & Mobile Computing*. He won the Ontario Graduate Scholarship for Science and Technology in 1997, the Ontario Graduate Scholarship in 1998, 1999, and 2000, and the Communication and Information Technology Ontario (CITO) graduate award in 2000. His research interests include wireless access techniques, resource management in wireless networks, smart antennas, 3G and 4G wireless systems, wireless Internet and multimedia services, and fixed wireless networks.