

User Based Call Admission Control Policies for Cellular Mobile Systems: A Survey ^{*}

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Abstract. Call admission control in mobile cellular networks has become a high priority in network design research due to the rapid growth of popularity of wireless networks. Dozens of various call admission policies have been proposed for mobile cellular networks. This paper proposes a new classification of user based call admission policies in mobile cellular networks. The proposed classification not only provides a coherent framework for comparative studies of existing approaches, but also helps future researches and developments of new call admission policies.

Keywords. Call Admission Control, Guard Channels, Wireless Networks

1 Introduction

In recent years, there has been a rapid growth in the number of users of mobile communication networks. However, the frequency spectrum allocated by the FCC (federal communication commission) to the mobile communication networks is very limited [1]. This limitation means that the frequency channels have to be reused as much as possible in order to support the many thousands of simultaneous calls that may arise in any typical mobile communication network. Thus, the efficient management and sharing of the frequency channels among numerous users become an important issue. In order to reuse the frequency channels, the cellular networks are introduced. In these networks, the geographical area covered by the network is divided into smaller regions, which are called cells. Each cell is serviced by a fixed server, called base station, located at its center, which is used to service the users located at that cell. A number of base stations are again linked to a central server called mobile switching center, which also acts as a gateway of the mobile communication network to the existing wire-line networks such as PSTN, ISDN, or internet. A base station communicates with users (mobile stations) through wireless links and with mobile switching centers through wire-line links. The model of such a network referred to as *cellular network* is shown in figure 1 [2].

In order for a mobile user to be able to communicate with other user(s), a connection usually must be established between the users. The establishment and maintenance of a connection in cellular networks is the responsibility of the base stations. In order to establish a connection, a mobile user must first specify its traffic characteristics and quality of service (QoS) requirements. This specification, may be either implicit or explicit depending on the type of services provided by the network. For example, in a cellular phone network, the traffic characteristics and QoS requirements of voice connections are known a priori to the base station, and therefore, they are usually specified implicitly in a connection request.

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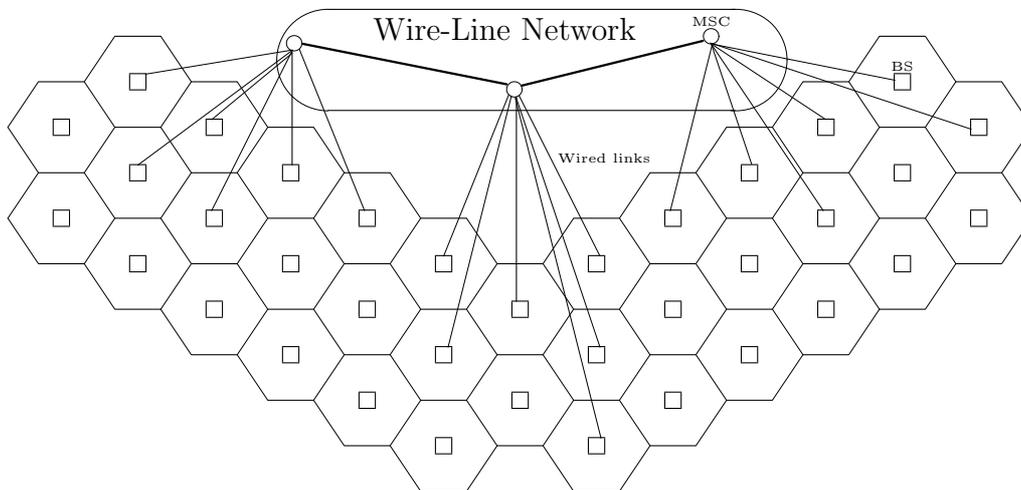


Fig. 1. System model of cellular networks.

The next generation wireless networks, such as wireless ATM networks, are expected to eventually carry multi-media traffics such as voice, mixed voice and data, image transmission, WWW browsing, email and etc, where the traffic characteristics and the QoS requirements of connections may not be known a priori to the base station. In these networks, mobile users must specify explicitly the traffic characteristics and the QoS requirements as a part of the connection request. Then, the base station determines whether it can meet the requested QoS requirements and, if possible, establish a connection.

When a call is originated and attempted in a cell, one of the channels allocated to the base station is used for the communication between the mobile station and the base station as long as channel is available. When all channels in a cell are in use while a call is attempted, then it will be blocked and cleared from the system. When a call gets a channel, it will keep the channel until its completion, or until mobile station moves out of the cell, in which case the used channel will be released. When the mobile station moves into a new cell while its call is ongoing, a new channel needs to be acquired in the new cell for further communication. This process is called *handoff* and must be transparent to the mobile user. During the handoff, if there is no channel is available in the new cell for the ongoing call, it is forced to terminate before its completion.

When a user moves from one cell to another, the base station in the new cell must take responsibility for all the previously established connections. A significant responsibility involves allocating sufficient resources in the cell to maintain the QoS requirements of the established connections. If sufficient resources are not allocated to the handoff calls, the QoS requirements may not be met, which in turn may result in forced termination of the connection. Since the forced termination of established connections is usually more objectionable than rejection of a new connection request, it is widely believed that a cellular network must give a higher priority to the handoff connection requests as compared to new connection requests. Handoff problems are expected to become more and more important since the size of cells in emerging cellular networks tend to be smaller, which implies that handoff would occur more frequently, to attain a higher capacity.

In order to satisfy the QoS requirements, call admission control algorithms are needed. The call admission control algorithms determine whether a call should be either accepted or rejected at the base station and assign the required channel(s) to the accepted call. This results in a distributed call admission control strategy which can be applied to every base station. Whenever a new call arrives, the call admission policy takes the call as input and based upon the current traffic conditions of network, decides whether or not to accept the user, as illustrated in figure 2.

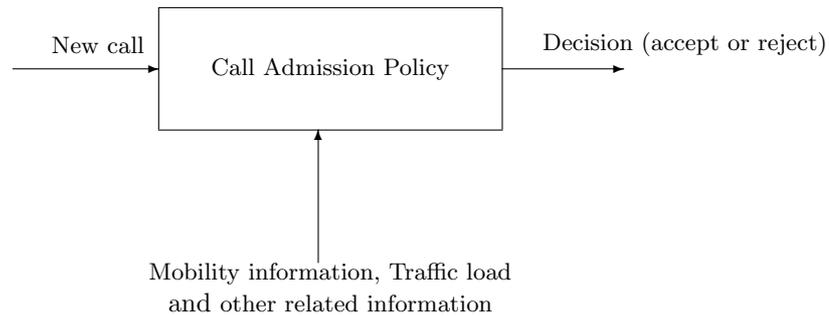


Fig. 2. The call admission control algorithm.

Call admission control in mobile cellular networks became a high priority in network design and research due to the rapid growth of popularity of wireless networks. A large number of various call admission policies have been proposed mobile cellular networks. However, despite years of research efforts, the call admission problem remains a critical issue and a high priority, especially given the perspectives of continually growing speed and size of future wireless networks. It is often difficult to characterize and compare various features among different policies. A good and detailed classification helps the researches and engineers to understand the similarities and differences among various schemes and decide which techniques are best suited for particular use. This paper proposes a new classification of call admission policies in mobile cellular networks. The proposed classification not only provides a coherent framework for comparative studies of existing approaches, but also helps in future researches and developments of new call admission policies.

The rest of this paper is organized as follows: Section 2 describes the call admission problem and presents the proposed classification. Section 3 gives the non-prioritized call admission policies and the prioritized call admission policies are given in section 4. Optimal policies are given in section 5 and section 6 concludes the paper.

2 Call Admission Control

The challenges in the wireless networks are to guarantee the QoS requirements while taking into account the limited number of channels and interference between them. The study of the different schemes to accept calls in communication networks is known as the call admission control problem. Call admission control for high speed networks such as ATM networks have been intensively studied in the last few years. There are two major differences between wireless and wire-line networks due to the link characteristics and user mobility. The transmission links for the broadband wire-line networks are characterized by high

transmission rates and very low error rates. In contrast, wireless links have a much smaller transmission rates and a much high error rates. The second major difference between the two networks is the user mobility. In wire-line networks, the user-network interface remains fixed throughout the duration of a connection whereas the user-network interface in a wireless environment may change throughout the connection. Due to the user mobility, call admission control becomes much more complicated in the wireless networks than wire-line networks. An accepted call that has not completed in the current cell may have to be handed off to another cell. During the handoff, the call may not be gain a channel in the new cell to continue its service due to the forced call termination. Thus, the new calls and handoff calls to be treated differently in terms of resource allocation. Since users tend to be much more sensitive to forced call termination (call dropping) than to the call blocking, handoff calls are normally assigned higher priority over the new calls.

Call admission control is one method to manage radio resources in order to adapt to the traffic variations. Call admission control denotes the process to make a decision for new admission according to the amount of the available resources versus users QoS requirements, and the effect upon the QoS of the existing calls imposed by new calls. Call admission control plays a very important role in cellular networks because it directly controls the number of users in the network and must be designed to guarantee the QoS requirements. The usual network performance indicators are the blocking probability of new calls, the dropping probability of handoff calls, the computation and communication overheads, and the total carried load. Good call admission control policies have to balance the dropping probability of handoff calls and the blocking probability of new call in order to provide the desired QoS requirements.

There has been much research into call admission control policies for cellular networks. A good call admission control algorithm must have the following features in order of importance.

1. Maximize channel utilization in a fair manner to all calls.
2. Minimize the dropping probability of connected calls.
3. Minimize the reduction of the QoS for the connected calls.
4. Minimize the blocking probability of new calls.

Call admission control policies can be divided into a number of different categories depending on the comparison basis. For example, when call admission control policies are compared based on decision policies, they can be divided into user(number)-based CAC (NCAC) and interference-based CAC (ICAC) policies [3–5]. NCAC policies accept/reject calls based on the number of occupied channels in the cell. In these policies, any new call will be blocked if the number of occupied channels exceeds a certain threshold. Each base station should always hold the number of communicating users by maintaining a variable on its memory. Using ICAC, a base station, by monitoring the interference on a call-by-call basis, determines whether or not a new call is acceptable. The new call is blocked if the observed interference level exceeds a CAC interference threshold. Each base station should measure the total power of received signals in the spreading bandwidth before despreading them. ICAC therefore requires overheads for base station hardware and complicates its architecture, while NCAC can be implemented by means of base station software.

In the rest of this paper, we present a new classification for user based call admission control policies. In the proposed NCAC schemes, we group the CAC algorithms into three main classes: prioritized, non-prioritized and optimal policies as given in figure 3. In non-prioritized CAC policies, all calls are accepted when the requested channels are free, while in prioritized CAC policies, one group of calls have a higher priority than other groups, for example, the handoff calls have the higher priority than new calls. In prioritized schemes, when the requested channels are not available, the call may be queued or rejected. Optimal CAC policies accepte/rejecte calls to maximize throughput of the network.

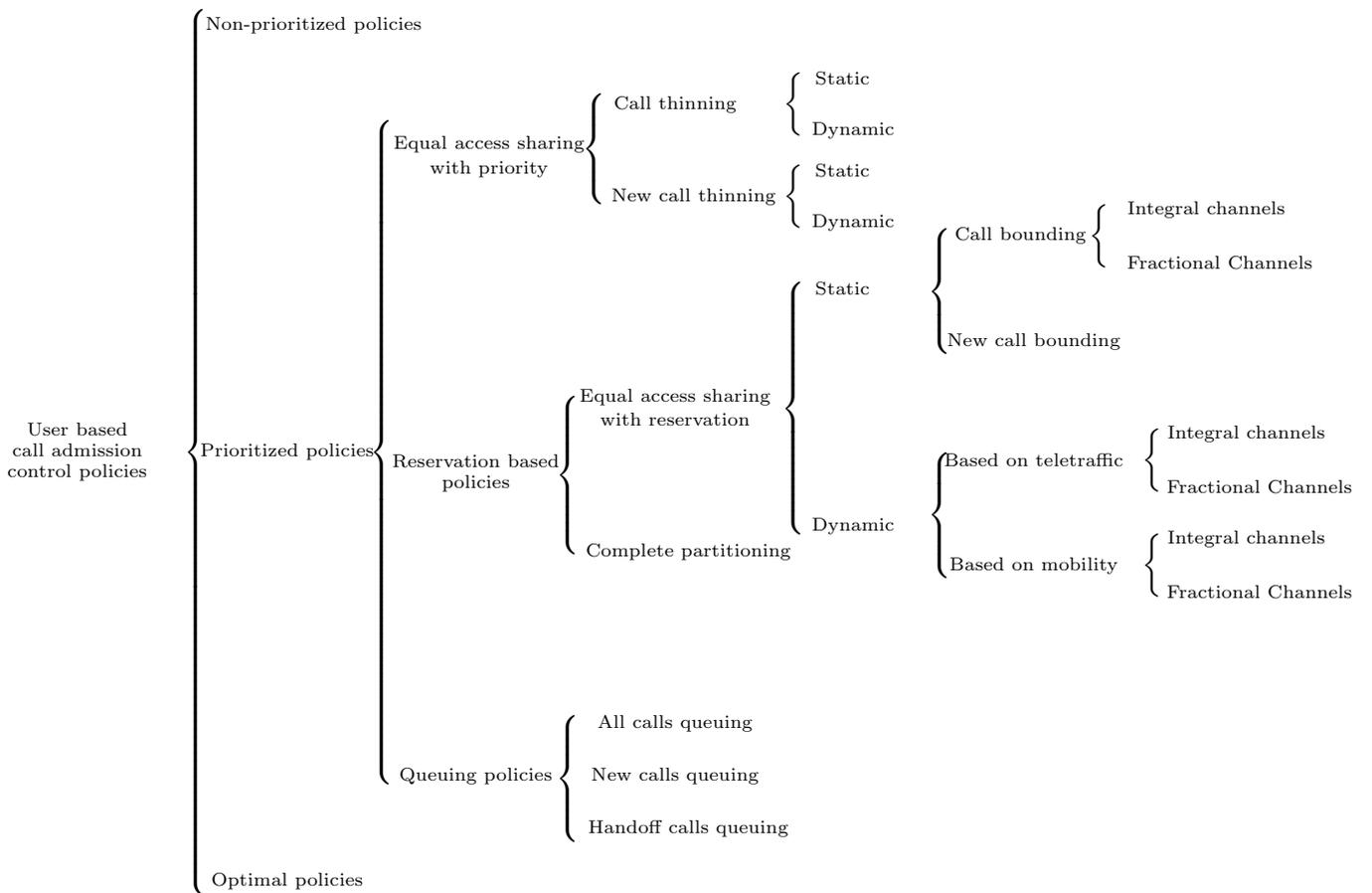


Fig. 3. Classification of user based call admission control algorithms.

Before we start presenting the NCAC schemes according to the proposed classification, a general framework for call admission control is developed and used throughout this survey. We consider network cells with N classes of calls $W = \{w_1, \dots, w_N\}$, and C full duplex channels. Each class w_i (for $1 \leq i \leq N$) consists of a stream of statistically identical calls with Poisson arrival at rate λ_i and independent identical exponentially distributed call holding times with mean $1/\mu_i$. Assume that all classes need only one channel for each call. Let c denotes the number of busy channels in the cell. The state space S of a cell is given by $S = \{c | c \leq C\}$. We define the admission policy $u : S \times W \rightarrow \{0, 1\}$, where $u(x, w)$ specifies that the probability of acceptance of calls of class w when the cell is in state x . At any time t , the decision to accept or reject calls of class w depends only on the current state of the cell or its neighboring cells. From the point of the call admission controller, the process can be modelled as a Markov process, where the transition rates between the states $x, y \in S$ for a call of class w , are given by

$$q(x, y) = \begin{cases} \sum_{w=1}^N u(x, w)\lambda_w & \text{if } y = x + 1 \\ x\mu & \text{if } y = x - 1 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where $\mu^{-1} = \sum_{i=1}^N \mu_i^{-1}$. Function $u(x, w)$ may be deterministic or stochastic (probabilistic), static or dynamic. Based on function $u(x, w)$, the call admission control policies can be divided into non-prioritized, prioritized, and optimal policies.

3 Non-prioritized Call Admission Control Policies

In these call admission control policies, no single class is treated any differently than any other classes. This is the simplest scheme and involving checking to guarantee that the requested bandwidth is available for the calls. If the bandwidth requirements can be met, then the call is accepted and the bandwidth is allocated. This policy always accepts calls as long as doing so leads to a state in the state space S , that is,

$$u(x, w) = \begin{cases} 1 & \text{if } x + 1 \in S \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

In this policy, the blocking probabilities of all traffic classes are equal and calculated using the Erlan-B formula [6, 7].

4 Prioritized Call Admission Control Policies

In prioritized call admission control policies, a priority is assigned to each class of calls. These priorities are implemented through function $u(x, w)$. For example, from the point of view of a mobile user, dropping of an ongoing call is less desirable than blocking of a new call. Therefore, in order to reduce the chances of unsuccessful handoff calls, the system assigns a higher priority to the handoff calls. Thus the function $u(x, \cdot)$ has a higher value for handoff calls than the new calls. The prioritized call admission policies can be divided into three groups *equal access sharing with priority*, *reservation based and queuing based policies*, and *queuing priority policies*, which are described in the rest of this section.

4.1 Equal Access Sharing with Priority (EASWP)

In this call admission control policy, all classes of calls have access to all channels but some classes have a higher priority than others. This priority is implemented through the use of function $u(x, w)p(x, w)$, where

$p(x, w)$ is the probability of accepting calls of class w when the cell is in state x . The reported EASWP policies can be classified as call thinning and new call thinning schemes, which are briefly described in the next two subsections.

4.1.1 Call Thinning Schemes

In these schemes, the state of system, x , is the number of busy channels in the cell. Call thinning This class of call admission schemes, in turn can be divided into two subclasses: static and dynamic, which are explained for two classes of calls, new calls and handoff calls, in the next two subsections.

4.1.1.1 Static Call Thinning Schemes

In these schemes, function $u(x, w)$ is determined based on a priori information and remain fixed during the operation of the network. In [8], a static call thinning scheme for two classes of calls is given. In this scheme, we have

$$u(x, w) = \begin{cases} p(x, w) & \text{if } x < C \\ 0 & \text{if } x = C. \end{cases} \quad (3)$$

The linear programming is used to determine the optimal values of $p(x, w)$. A restricted version of this scheme, which is called fractional guard channel scheme, is given in [9]. In this scheme, the handoff calls have higher priority over the new calls. This scheme accepts new calls with certain probability that depends on the channel occupancy of the cell and accepts the handoff calls when the cell has free channels. In this scheme, we have

$$u(x, w) = \begin{cases} 1 & \text{if } x < C \text{ and } w = \text{handoff calls} \\ p(x) & \text{if } x < C \text{ and } w = \text{new calls} \\ 0 & \text{if } x = C. \end{cases} \quad (4)$$

Since $p(x)$ only appears when the new calls arrives, $p(x)$'s are called new call admission probabilities. The idea behind this scheme is to smoothly throttle the new call stream as the network traffic is building up. Thus, when the network is approaching the congestion, the accepted new calls becomes thinner. Due to the flexible choice of new call admission probabilities, this scheme can be made very general. The most disadvantage of this scheme is that no algorithm is given to find $p(x)$ s. In order to find $p(x)$, a restricted version of this scheme called uniform fractional guard channel policy is introduced [10]. In this scheme, the new call admission probabilities are independent of channel occupancy. Thus, in this scheme, we have

$$u(x, w) = \begin{cases} 1 & x < C \text{ and } w = \text{handoff calls} \\ p & x < C \text{ and } w = \text{new calls} \\ 0 & x = C. \end{cases} \quad (5)$$

4.1.1.2 Dynamic Call Thinning Schemes

In dynamic call thinning schemes, function $u(x, w)$ is adapted based on information gathered during the operation of the network. Some of the dynamic call thinning algorithms are reported in [11–14]. A dynamic call thinning scheme for multi-media cellular network is presented in [11]. In this scheme, calls are classified on the basis of channel requirement and with each class a priority is associated. This scheme collects calls in a time period and then accepts calls with the higher priorities. In [12, 13], a

multi-media cellular network with two traffic classes are considered and the call admission problem is formulated as a semi-Markov decision process problem. Since, it is too complex to have a closed form solution for this semi-Markov decision process, Q-learning [12] and neuro-dynamic programming [13] are used to adapt the function $u(x, w)$. In [14], a call admission scheme called stable dynamic call admission control scheme is suggested. The aim of this scheme is to maximize the channel utilization (minimize the new call blocking probability) subject to a hard constraint on the dropping probability of handoff calls. In this scheme, status information are exchanged periodically between neighboring cells, and even next neighboring cells if necessary. The exchanged information includes the channel occupancies and the new call arrival rates. Each cell updates its acceptance ratio (the maximum fraction of new calls to be accepted in the cell) in the next control period at the beginning of that period. The control action is obtained by solving system of equations which specifies the average dropping probability of handoff calls must be equal to the QoS of the system. In [15], a learning automata based algorithm is given to adjust the value of p , in which a learning automaton is associated to each cell. In this algorithm, when a handoff call arrives, it is accepted as long as there is a free channel. If there is no free channel, the handoff call is blocked. When a new call arrives to a particular cell, the learning automaton associated to that cell chooses one of its actions. The learning automaton accepts new calls with probability p as long as there is a free channel and rejects new call with probability $1 - p$. If action ACCEPT is selected by the automaton and the cell has a free channel, then action ACCEPT is rewarded. If there is no free channel to be allocated to the arrived new call, the call is blocked and the action ACCEPT is penalized. When the automaton selects action REJECT, the adaptive UFG computes an estimation of the dropping probability of handoff calls (\hat{B}_h) and uses it to decide whether or not accept new calls. If the current estimate of dropping probability of handoff calls is less than the given threshold p_h and there is a free channel, then the new call is accepted and the action REJECT is penalized; otherwise, the new call is rejected and the action REJECT is rewarded. This algorithm cannot maintain the upper bound on the dropping probability of handoff calls. This problem may be due to the existence of delay in the cellular network, because the selected action of learning automaton is immediately rewarded/penalized. Since the effect of the estimated new call admission probability is specified after a time period, then the reward/punishment of learning automaton must be given in the end of that period. In order to overcome this problem, an algorithm is given in [16], in which the action probability vector of learning automaton is adjusted upon arriving the next new call. This algorithm uses a learning automaton to accept/reject new calls and a pre-specified level of dropping probability of handoff calls is used to penalize/reward the action selected by the learning automaton. This algorithm accepts new calls as long as the dropping probability of handoff calls is below the pre-specified threshold. In [17], it is shown that this algorithm finds the optimal value of the of UFG's Parameter.

4.1.2 New Call Thinning Schemes

Below we explain the only reported new call thinning scheme [18]. In this scheme, the state of system, x , is the number of ongoing new calls in the cell. For the sake of simplicity assume that we have two classes of calls: new calls and handoff calls. This scheme, which limits the new calls in the system, gives a higher priority to the handoff calls over the new calls. This scheme accepts new calls with certain probability that depends on the number of ongoing new calls in the cell and accepts the handoff calls when the call has free channels. In this scheme, we have

$$u(x, w) = \begin{cases} 1 & \text{if } x < C \text{ and } w = \text{handoff calls} \\ p(x) & \text{if } x < C \text{ and } w = \text{new calls} \\ 0 & \text{if } x = C. \end{cases} \quad (6)$$

4.2 Reservation Based Call Admission Control Policies

In reservation based call admission control policies, some of the channels allocated to the cell are reserved for the higher priority calls. In the reservation based call admission control policies, we have $u(x, w) = 0$ for some x and w . In these call admission control policies, all classes of calls are accepted equally within a specified bandwidth of the maximum channel capacity that depends on the given class. Once the available channel capacity has been used, only calls that are of a high priority will be accepted to use the remaining (reserved) channels (bandwidth). This has the effect of prioritizing a traffic class above the other traffic classes. In the reservation based policies, classes of calls can be grouped and fix a threshold for each group. When restricted to simple form, these policies dedicate a certain number of channels for each group and the remaining channels are shared among all groups. To define a simple form for these policies, we form W groups, G_1, \dots, G_W , such that each w belongs to only one group G_w . The reservation based policies can be stated as

$$u(x, w) = I\{x \leq T_w\} \wedge I\{x + 1 \in S_{G_w}\}, \quad (7)$$

where T_w is the maximum channel capacity for calls of class w in group G_w and S_{G_w} is the set of channels associated to group G_w . These policies can be divided into two main groups: *equal access sharing with priority* (EASWR) and *complete partitioning schemes*, which are explained in the following subsections.

4.2.1 Equal Access Sharing with Reservation (EASWR)

In these call admission control policies, we have $S = S_{G_1} = S_{G_2} = \dots = S_{G_W}$. Thus, all classes can use any channel and are accepted equally within a specified bandwidth of the maximum channel capacity. Once the available channel capacity has been used, only calls that are of high priority will be accepted to use the remaining (reserved) bandwidth. This has the effect of prioritizing one class above the other classes, that is,

$$u(x, w) = I\{x \leq T_w\} \wedge I\{x + 1 \in S\}, \quad (8)$$

where T_w is the maximum channel capacity for calls of class w . Based on the manner used for determination of the values of T_w s, the EASWR policies can be divided in two main groups: static and dynamic EASWR schemes. In static EASWR schemes, values of T_w s are determined based on the a priori information about the network and remain unchanged during the operation of the network while in dynamic EASWR schemes, T_w s are adapted during the operation of the network. In what follows, static and dynamic EASWR schemes are briefly described.

4.2.1.1 Static EASWR Schemes

In static schemes, T_w s are determined based on a priori information and are fixed during the operation of the network. Static EASWR schemes are very simple in that no communication and computation overheads are involved. However, such schemes are not flexible to handle the changing traffic situations. Since, these schemes don't use the traffic information in the current cell and/or its neighboring cells,

hence they cannot adapt the real-time network conditions. The static EASWR schemes can be divided into two main groups: *call bounding* and *new call bounding* schemes. In the call bounding schemes, the call admission is based on the number of ongoing calls (number of busy channels) in the cell while in the new call bounding schemes, the call admission is based on the number of ongoing new calls in the cell.

4.2.1.1.1 Call Bounding Schemes In the call bounding schemes, admission of a new call is based on the number of ongoing calls in the cell, independent of type of calls. In other words, the state x of a cell is defined as the number of busy channels in the cell. Based on the values of T_w s, the call bounding schemes can be divided into two schemes: *reserving integral number of channels* and *reserving fractional number of channels*. In the reserving integral number of channels, all T_w s are integer values while in reserving fractional number of channels, at least one of T_w 's are fractional numbers. These schemes are briefly described below.

Reserving Integral Number of Channels In the reserving integral number of channel schemes, all T_w s are integers. In these schemes, function $u(x, w)$ is equal to either 0 or 1. When only two groups G_1 and G_2 (one for new calls and the other for handoff calls) are considered, this scheme is referred to as *guard channel policy*, or *cutoff priority policy* in which a fixed number of channels is reserved in each cell exclusively for handoff calls [19]. Under such policy, new calls and handoff calls are treated equally on a first-come first-served basis for channel allocation until a predetermined channel utilization threshold is reached. At this point, new calls are simply blocked and only handoff call requests are accepted. In other words, a new call is accepted if $c < C - T_1$, where $T_1 \geq 0$ is the number of channels reserved specifically for handoff (guard channels), that is,

$$u(x, w) = \begin{cases} 1 & \text{if } x < C \text{ and } w = \text{handoff calls} \\ 1 & \text{if } x < T_1 \text{ and } w = \text{new calls} \\ 0 & \text{if } x = C. \end{cases} \quad (9)$$

It has been shown that there is an optimal threshold T_1^* in which the blocking probability of new calls is minimized subject to the hard constraint on the dropping probability of handoff calls [9]. Algorithms for finding the optimal number of guard channels are given in [9, 20, 21]. In [20], also an algorithm is given to find the optimal number of guard channels in one cluster of multi-cell system. In [22], an algorithm is given to find the optimal number of guard channels in a general multi-cell networks, which minimizes the weighted average of dropping probability of handoff calls in a cluster while satisfying the pre-specified QoS for new calls and co-channel interference constraints. In [23], two traffic classes of voice and transactions are considered and static guard channel scheme are proposed to maintain the upper bound of dropping probability of handoff transaction calls. In this approach, $(C - T_1)$ guard channels are reserved for handoff transaction calls, but new calls and handoff voice calls have the same priority. Thus, this scheme fails to maintain the upper bound for dropping probability of handoff voice calls. In order to maintain the upper bound for dropping/blocking probability for different classes of calls, multi-threshold schemes are introduced.

In [24], dual-threshold reservation (DTR) scheme is given for integrated voice/data wireless networks. In DTR scheme, three classes of calls, data calls (both new and handoff calls), new voice calls and handoff voice calls in increasing order of level of QoS are considered. The basic idea behind the DTR scheme is to use two thresholds, one for reserving channels for handoff voice calls, while the other is used to block data calls into the network in order to preserve the blocking performance of voice calls in terms of the

dropping probability of handoff calls and the blocking probability of new calls, that is,

$$u(x, w) = \begin{cases} 1 & \text{if } x < C \text{ and } w = \text{handoff voice calls} \\ 1 & \text{if } x < T_2 \text{ and } w = \text{new voice calls} \\ 1 & \text{if } x < T_1 \text{ and } w = \text{new data calls or handoff data calls} \\ 0 & \text{if } x = C. \end{cases} \quad (10)$$

DTR assumes that the bandwidth requirement of voice and data are the same. The equations for blocking probabilities of DTR are derived using a two-dimensional Markov chain and the effect of different values for number of guard channels on dropping and blocking probabilities are plotted, but no algorithm for finding the optimal number of guard channels is given. In [25], an algorithm is given to find the optimal values of T_1 and T_2 for a single cell case and in [26], an algorithm is given to find the optimal values of T_1 and T_2 in multi-cell system. In [?], multi-threshold guard channel scheme is introduced, in which

$$u(x, w) = \begin{cases} 1 & \text{if } x < T_w \\ 0 & \text{otherwise.} \end{cases} \quad (11)$$

In [?], an algorithm is also given to find the optimal values of T_w 's for single cell case and in [27], an algorithm is proposed to find the optimal values of T_w 's in multi-cell network.

In reserving integral number of channels, a number of channels are exclusively reserved for highest priority calls which results in less channels available to lowest priority calls and hence the total carried traffic suffers. In these schemes, if only the blocking probability of highest priority calls is considered, these schemes give very good performance, but the blocking probability of lowest priority calls is degraded to a great extent. This effect can be degraded by reserving fractional number of channels.

Reserving Fractional Number of Channels In reserving fractional number of channels, T_w s are real numbers. In these schemes, the call admission controller have more control on both the dropping probability of handoff calls and the blocking probability of new calls. When only two groups G_1 and G_2 (one for new calls and the other for handoff calls) are considered this policy is referred to as *limited fractional guard channel scheme* (LFG) in which a fractional number of channels is reserved in each cell exclusively for handoff calls [9]. The LFG scheme uses an additional parameter π_1 and operates the same as the guard channel policy except when T_1 channels are occupied in the cell, in which case new calls are accepted with probability π_1 , that is,

$$u(x, w) = \begin{cases} 1 & \text{if } x < C \text{ and } w = \text{handoff calls} \\ 1 & \text{if } x < T_1 \text{ and } w = \text{new calls} \\ \pi_1 & \text{if } x = T_1 \text{ and } w = \text{new calls} \\ 0 & \text{if } x = C. \end{cases} \quad (12)$$

It has been shown that there is an optimal pair (T_1^*, π_1^*) , which minimizes the blocking probability of new calls subject to the hard constraint on the dropping probability of handoff calls [9].

4.2.1.1.2 New Call Bounding Schemes In new call bounding schemes, new calls are accepted if the number of channels used by new calls is less than a threshold (bound for new call) provided that the cell has enough channels for allocating to the incoming new calls. In other words, the state, x , of a cell is defined as the number of ongoing new calls in the cell. In [18], a new call bounding scheme is given in which T_w s are integers. In this scheme, when a new call arrives, if the number of new calls in a

cell exceeds a threshold then the new call is blocked; otherwise it will be accepted and the handoff call is rejected only when all channels in the cell are occupied [18]. The idea behind this scheme is that we would rather accept fewer new calls than dropping the ongoing calls in the future, because customers are more sensitive to the call dropping than the call blocking. In [28], a new call bounding scheme is given for integrated voice/data wireless networks. In this scheme, it is assumed that the number of ongoing data calls always is constant. This scheme accepts the incoming voice request if the number of voice connections is less than the voice threshold T_1 . Since the number of data connections is fixed, there is no call admission control for data connections. In [28], no algorithm is given to determine the optimal value of T_1 .

4.2.1.2 Dynamic EASWR Schemes

According to the information theory, available information should be used to achieve better performance, therefore dynamic reservation schemes are proposed to overcome the disadvantages of the static reservation schemes. In EASWR schemes, function $u(x, w)$ is adapted according to the some available information. In dynamic EASWR schemes, the number of the channels are allocated and reserved dynamically using *traffic analysis* and *prediction of mobile terminal movement*. These schemes are briefly described in the next three subsections.

4.2.1.2.1 Dynamic EASWR Schemes Based on Teletraffic Analysis In dynamic EWASR schemes based on teletraffic analysis, function $u(x, w)$ is adapted based on the estimated traffics. Since all ongoing calls in the neighboring cells are potential handoff calls to the test cell, in these schemes the handoff arrival rate is estimated as a function of the number of ongoing calls in the neighboring cells. In these schemes, the number of reserved channels can be an integral number or a fractional number. The reported schemes which fall this category are briefly described below.

Reserving Integral Number of Channels : In these schemes, an integral number of channels is reserved for higher priority calls. Some of the reported schemes are briefly described below. These schemes consider two traffic classes, new calls and handoff calls unless explicitly stated. The *linear weighting scheme* is given in [29, 30] and uses the mean number of ongoing calls in the neighboring cells, i , within a maximum cell distance d from the test cell in determining of the call admission. Let S_d denotes the set of cells in a maximum cell distance d from the test cell and c_i denotes the number of ongoing calls in the neighboring cell i . In this scheme, the state of the system at each time instant is defined as

$$x = \left[\frac{1}{|S_d|} \sum_{i \in S_d} c_i \right].$$

In linear weighting scheme, the new calls are only accepted to the originating cell if

$$u(x, w) = \begin{cases} 1 & \text{if } x < C \text{ and } w = \text{handoff calls} \\ 1 & \text{if } x < T_1 \text{ and } w = \text{new calls} \\ 0 & \text{if } x = C. \end{cases} \quad (13)$$

Note that the guard channel scheme is a special case of this algorithm where $S_d = i$. In [31, 32], a scheme called *weighted sum scheme* is given. This scheme uses the weighted sum of the number of ongoing calls in the test cell and in the neighboring cells in determining the admission. Let c_i be the mean number

of ongoing calls in the neighboring cells with distance i and p_i be the weight of these cells such that $\sum_{i=0}^{\infty} p_i = 1$ and $p_i \geq 0$ (for $i \geq 0$). The state of system in weighted sum scheme at each time instant is defined as

$$x = \left[\sum_{i=0}^{\infty} p_i c_i \right].$$

In this scheme, the new calls are only accepted to the originating cell if

$$u(x, w) = \begin{cases} 1 & \text{if } x < C \text{ and } w = \text{handoff calls} \\ 1 & \text{if } x < T_1 \text{ and } w = \text{new calls} \\ 0 & \text{if } x = C. \end{cases} \quad (14)$$

The optimal value of weights p_i can be determined experimentally. The *distributed call admission scheme*, which is given in [33], does not need the status information exchange upon each call arrival (new call and handoff). Rather, it only requires the exchange of such information periodically. The admission control algorithm calculates the maximum number of calls that can be accepted in the test cell without violating the QoS of the existing calls in that cell as well as calls in its neighboring cells. One of the main features of this scheme is its simplicity in that the admission decision can be made in real time and does not require much computational effort but this scheme cannot always guarantee the target call dropping probability. In [34], a dynamic guard channel scheme is introduced in which each base station dynamically adapts the number of channel to be reserved based on the current estimates of the rate at which mobiles in the neighboring cells are likely to incur a handoff into this cell. The objective of the adaptation algorithm is to maintain a specified level of QoS for handoff calls despite temporal fluctuations in the traffic into the cell. The determination of the number of channels to be reserved is based on an analytical model which relates number of reserved channels to the dropping probability of handoff calls and the blocking probability of new calls. In [35], the number of channels that must be reserved is estimated according to the requested bandwidth of all ongoing connections. Each base station keeps monitoring the dropping probability of handoff calls and the utilization of channels in its cell. Then based station according to this information adjust the number of guard channels. In [36], a call admission algorithm is proposed in which when a new or a handoff call arrives at the test cell, a number of channels in the neighboring cells is reserved. The number of channels to be reserved varies dynamically depending on the number current ongoing calls in the test cell and its neighboring cells. In [37], the authors have proposed a scheme based on prediction of the probability that a call will be handed off to a certain neighboring cell from aggregate history of handovers in each cell and determines the number of reserved channels. In this scheme, each base station records the number of handoff failures and adjusts the reservation by changing the estimation window size. In [38], a call admission algorithm for multi-rate personal communication networks is given. In this algorithm the number of channels that must be reserved is determined periodically based on the estimated parameters, such as handoff rate. In the beginning of each period, the traffic parameters are estimated and it is assumed that for a given period, traffic parameters are constant. In this scheme, when the number of occupied channels reaches the threshold T_1 , the cell reserves a resource in the neighbors for which the probability of transition is high. If they have free channels, the reservation takes place immediately. Otherwise, the algorithm waits for a free channel. In [39], two dynamic EASWR algorithms are given for wireless networks that support several traffics, voice, data, and video applications, each with different channel requirements. The objective of these algorithms is to accept all handoff calls. Then the base station accepts new calls if and only if the additional channels need to accept all incoming handoff calls (the number of channels to be reserved) and this new call is available. The number of reserved channel is determined according to the estimation of the exact arrival time and channel requirements of

future handoff calls. An extension of guard channel scheme is given in [40, 41]. This scheme works same as guard channel when a new call arrives and $x < T_1$ or $x = C$; when $T_1 \leq C$, the algorithm estimates the dropping probability of handoff calls during a period. Then the algorithm accepts new call if the estimated dropping probability of handoff calls is less than the predetermined QoS; otherwise reject the new call. A dynamic channel reservation algorithm, which is presented in [42], the number of channel to be reserved in each cell is determined dynamically based on the number of ongoing calls in the neighboring cells. This scheme ensures that QoS is maintained in all cells. In [43, 44], two learning automata based algorithms are given that adjust the number of channels to be reserved in the cell according the traffic of the cell and the predefined QoS.

Reserving Fractional Number of Channels : In these schemes unlike reserving an integral number of channels schemes, a fractional number of channels is reserved for higher priority calls. In these schemes, T_w s are time varying and determined based on the estimated traffics. In [45], a call admission algorithm is given, in which when a new or handoff call arrives at a neighboring cell, number of channels that must be reserved in the test cell is increased by a fraction amount and when a call is completed at or moved out of the neighboring cells, the number of reserved channels is decreased by the same fractional amount. In [46], a call admission algorithm, which is called *population-based channel reservation scheme* is presented. This scheme dynamically adjusts the number of channels that must be reserved for handoff calls according to the amount of cellular traffic in its neighboring cells. Assume that cell i have n_i neighboring cells. Whenever a call which consumes b channels is accepted into cell j as either a newly call or a handoff call, the base station of the cell requests a fractional channel reservation for the amount of b/n_j to each of its n_j neighboring cells. Whenever this call is leaving the cell either by call completion or by handoff into its neighbor, the base station requests a fractional channel release for the same amount as requested for the reservation to each of its n_j neighboring cells, even to the cell into which this call is handed over. This step is to inform the neighborhood of appearance and disappearance of a potential handoff. Each base station in a cellular network maintains a counter that records transactions for fractional channel reservation or release requests from its neighboring cells. Every time it receives a fractional channel reservation request or a release request, it increments or decrements the counter by the requested amounts, respectively. In [47–49], three adaptive LFG algorithm based upon continuous action-set learning automata are proposed. These algorithms adjust the number of channels to be reserved in the cell according the traffic of the cell and the predefined QoS. It is shown that the algorithm given in [49] finds the optimal number of channels that must be reserved.

4.2.1.2.2 Dynamic EASWR Schemes Based on Mobility The most salient feature of the mobile wireless network is the mobility, which can be used for adjusting the T_w s. Since the handoff occurs when the mobile users are moving during the call connection, thus good call admission control algorithms should consider the mobility pattern. Hence, in order to make a reservation schemes effectively adapt to the network traffic situations, the user mobility information must be deployed. In these schemes, each base station adjusts the reservation by employing the mobility information. The mobility pattern is determined by many factors such as destinations of mobile users, the layout of the network, and the traffic condition in the network. Since it is not easy to specify the mobility pattern of each mobile user in detail, therefore the statistical mobility patterns of users are more useful. Based on the values of thresholds, T_w s, these schemes can be divided into two groups: reserving integral number of channels and reserving fractional number of channels, which are briefly described below,

Reserving Integral Number of Channels In these schemes, an integral number of channels is reserved for higher priority calls. Some of the reported schemes are briefly described below. Concept of *shadow cluster* is introduced in [50], which estimates the future resource requirements based on the current movement pattern of the mobile users. The fundamental idea of the shadow cluster concept is that as an active user travels to other cell, the region of influence also moves. The base stations currently being influenced are said to form a shadow cluster, because the region of influence follows the movement of the active mobile terminal like a shadow. However, the strength of this scheme depends on the accuracy of the knowledge of users movement patterns, such as trajectory of a mobile user, which is difficult to predict in real time systems. In [51], a call admission algorithm, which is called *integral mobility based channel reservation scheme* has been presented. In this scheme, mobile users are classified in two classes according to their velocities: high and low speed users. Thus the average cell dwell time of high speed users are shorter than that of the low speed users. Based on the velocity of each mobile user, the handoff probability of each class is predicted and the number of channels that must be reserved is determined. It is also noted that the better performance will be achieved if this scheme and a new call bounding scheme are combined [51]. In [52], a dynamic reservation scheme for multimedia cellular networks is introduced in which the handoff calls have a higher priority than the new calls. The prerequisite of this scheme is that base stations can estimate future trajectory of mobile computers with high degree of accuracy, which is possible in today's increasing improved position location techniques. This scheme uses the Kalman filter to predict the next cell for every mobile computer.

Reserving Fractional Number of Channels In reserving fractional number of channels, T_w s are real numbers. In these schemes, the call admission controller have more control on both the dropping probability of handoff calls and the blocking probability of new calls since the rounding of T_w 's lost some information. In order to have more control on the dropping probability of handoff calls, *fractional mobility based channel reservation scheme* is given in [51]. In this scheme, mobile users are classified in two classes according to their velocities: high and low speed users. Thus the average cell dwell time of high speed users are shorter than that of the low speed users. Based on the velocity of each mobile user, the handoff probability of each class is predicted and values of $T - w$'s are determined.

One critical issue in all reservation based call admission control policies is how the reservation is made. In traditional guard channel policy, the number of guard channels is determined based on the priori knowledge of the cell traffic and the QoS requirements. Obviously, the performance will degrade if the cell traffic is not conformal to the priori knowledge; thus it will be better to use dynamic reservation schemes: adjusting the number of guard channels with the network traffic. In order to determine an optimal or near optimal value for number of guard channels one first answer the following question: when do reserve channels for incoming handoff calls? If the reservation is made at time when it is needed, the resulting scheme will definitely achieve the best performance. However, such timing will be very difficult, if it is not impossible, to acquire. Since the reservation is a waste of resources if it not used by handoff calls, the shorter the time the reservation is actually used (reservation time), the better performance will be achieved.

4.2.2 Complete Partitioning Policies

Complete partitioning policies are subsets of reservation based call admission policies. In these policies, we have $S = S_{G_1} \cup S_{G_2} \cup \dots \cup S_{G_w}$. Complete partitioning policies partition the channels among the different classes of calls by dedicating a certain number of channels to each class. This policy takes place when the threshold point for traffic class w is inside the state space, i.e. $T_w \in S$. These policies isolate each class

of calls and the resulting process is simply the aggregation of N independent $M/M/T_w/T_w$ processes. In [53], a cellular system is considered that supports two traffic types of voice (constant-rate) and data (variable-rate). In this scheme, voice calls have a higher priority than the new calls. The channels in each cell is partitioned into two subsets, one for voice calls and the other for data calls. Each partition uses the standard LFG policy to accept/reject new calls in that class. In [54], a dynamic channel allocation for multimedia cellular networks is given. This algorithm uses the guard channel scheme for maintaining the level of QoS and works the same as the guard channel scheme when a new or handoff call arrives, but when a call is terminated or completed, it differs from the guard channel policy. If a call that uses a guard channel is terminated or completed, then that channel is reserved for future incoming handoff calls. On the other hand, if a call that uses an ordinary channel is terminated or completed, then the bandwidth adaptation, which is the allocation of freed bandwidth to the ongoing calls, is applied. In order to allocate the freed bandwidth to the ongoing calls, a Lagrangean relaxation procedure is used that leads to a sub-optimal solution. In [55], channels assigned to a cell are divided into two groups: ordinary and guard channel groups. The new calls are accepted if the ordinary channel group has free channel; otherwise the call will be blocked. For handoff calls, three different strategies are used: 1) first guard channel group and then the ordinary channel group is selected, 2) first ordinary channel group and then the guard channel group are selected, and 3) randomly one of the preceding strategies is selected. In order to improve the blocking probability of new calls without trading off the dropping probability of handoff calls, an algorithm is given in [55]. In this algorithm, if all channels in the ordinary channel group are occupied at the arrival time of a new call and there is at least one free channel in guard channel group, then any free guard channel can temporarily be lent to the ordinary channel group to prevent the new call to be blocked. Such transferring can only be carried out if the base station can predict that there is no handoff attempts from neighboring cell, while the borrowed channel is used for the new call. This prediction is done with the aid of power measurements.

4.3 Queuing Priority Schemes

These schemes reduce the blocking probability of new calls and the dropping probability of handoff calls by employing a queuing mechanism. In queuing priority schemes, calls of each class are accepted whenever there is free channels for that class. When there is no free channels for a class, calls may be queued and calls of other classes are blocked and cleared from system. One key point of using queuing in call admission control algorithms is that the service differentiation could be managed by modifying the queuing discipline. For example, instead of FIFO queuing strategy, other prioritized queuing discipline can be used to maintain priority level in each service class. The another key point is the mobility of the users, which results difficulties in management of queue. These schemes consider two traffic classes, new calls and handoff calls. Based on the type of calls that is queued, these schemes are divided in three groups: *new call queuing schemes*, *handoff call queuing scheme* and *all call queuing schemes*. Some of the reported schemes are briefly described below.

4.3.1 New Call Queuing Schemes

In a new call queuing scheme, a certain number of channels is reserved in each cell exclusively for handoff calls. In new call queuing schemes, the new calls and the handoff calls are treated equally on a first-come first-served basis for channel allocation until the number of occupied channels in the cell becomes T_1 . When the predetermined channel utilization threshold, T_1 , is reached, new calls are queued and only

handoff call requests are accepted. In other words, a new call is accepted if $c < C - T_1$, where $T_1 \geq 0$ is the number of channels reserved specifically for handoff (guard channels), that is,

$$u(x, w) = \begin{cases} \text{accept} & \text{if } x < C \text{ and } w = \text{handoff calls} \\ \text{accept} & \text{if } x < T_1 \text{ and } w = \text{new calls} \\ \text{queue} & \text{if } x \geq T_1 \text{ and } w = \text{new calls} \\ \text{reject} & \text{if } x = C. \end{cases} \quad (15)$$

The only reported new call queuing scheme is given in [56]. In this scheme, when the number of free channels is less than the number of guard channels, the new calls are queued. It is pointed out that the blocking probability of a new calls can be drastically reduced by reserving some channels for handoff calls and using a queuing mechanism for new calls.

4.3.2 Handoff Calls Queuing Schemes

Handoff queuing schemes reserves a number of channels for use of handoff calls. In these schemes, the new calls are serviced as same as handoff calls until the number of free channels becomes less than the number of reserved channels ($C - T_1$). When the number of occupied channels is greater than *threshold* T_1 , new calls are blocked and handoff call requests are accepted. When all channels are occupied, the handoff calls are queued, that is

$$u(x, w) = \begin{cases} \text{accept} & \text{if } x < C \text{ and } w = \text{handoff calls} \\ \text{queue} & \text{if } x = C \text{ and } w = \text{handoff calls} \\ \text{accept} & \text{if } x < T_1 \text{ and } w = \text{new calls} \\ \text{reject} & \text{if } x \geq T_1 \text{ and } w = \text{new calls}. \end{cases} \quad (16)$$

Hong and Rappaport analyzed handoff queuing scheme with an infinite buffer for handoff calls [19] and this scheme with finite buffer is analyzed in [57]. The extension of handoff queuing scheme with finite buffer size to multi-class of calls is proposed in [58]. In [59], a handoff call queuing scheme is introduced which reserves no channels for handoff calls. In this scheme, when a new call arrives and all channels are busy, then the call will be blocked; when a handoff call arrives and all channels are busy, the call will be queued. Both types of calls will be accepted if there are any free channels. When a channel become free, then a handoff call from the queue, if queue is not empty, will be serviced. In [59], also some queuing discipline such as first-in first out, most critical first have been proposed. In [60], a dynamic channel reservation scheme with handoff queuing is introduced. In this scheme, the number of channels to be reserved is adjusted based on the handoff traffic and the current number of reserved channels. In [61], a dynamic channel reservation scheme with handoff queuing is introduced. In this scheme, the number of channels to be reserved is adjusted based on the occupied channels in the neighboring cells. It must be pointed out that queuing of handoff calls is more sensitive to delay (time between request and the time for allocation of channels) in the service than queuing of new calls, because as mobile users move the signal strength decreases and the call may be dropped. However, this delay depends on the speed of the mobile user.

4.3.3 All Calls Queuing Schemes

These schemes work as same as guard channel scheme when the number of occupied channels in the cell is less than T_1 . When the number of occupied channels is equal or greater than T_1 , new calls are queued

and only handoff call requests are accepted. When all channels are occupied, the handoff calls are also queued, that is

$$u(x, w) = \begin{cases} \text{accept} & \text{if } x < C \text{ and } w = \text{handoff calls} \\ \text{queue} & \text{if } x = C \text{ and } w = \text{new calls} \\ \text{accept} & \text{if } x < T_1 \text{ and } w = \text{new calls} \\ \text{queue} & \text{if } x \geq T_1 \text{ and } w = \text{new calls} \end{cases} \quad (17)$$

In [57], a call admission scheme is introduced in which the value of T_1 is equal to C . In this scheme, the new calls are put after all handoff calls in the queue and the queue is serviced in the FIFO manner. When the queue is full, then all incoming calls will be blocked. In [57], a rearranging mechanism is also introduced in which when the queue is full, then the last new call is pushed out from the queue and the incoming handoff call will be placed after the last handoff call. In [62], a call admission scheme is given in which all calls are queued with certain rearrangements in the queue.

5 Optimal Call Admission Policies

Let assign a cost to each blocked call, low cost for new calls and high cost for handoff calls, the optimal policy is the one that finds $u(x, w)$ in such a way that the cost is minimized. In these policies, the call admission is formulated as a Markov decision process and actions of this Markov decision process are used as function $u(x, w)$. In [63], value iteration algorithm of Markov decision process has been used throughout as a technique to search for the optimal policy, that is, the policy which minimizes a weighted blocking criteria. In [64, 65] a call admission control algorithm is given which focuses the forced termination probability (call dropping probability) as the main QoS requirement. In this approach the cellular system is modelled using semi-Markov decision process. The linear programming method for solving semi-Markov decision process is employed to find out the optimal call admission control decision in each state. In [66], the call admission problem in dual-mode cellular networks is formulated as a Markov decision process and the linear programming is used for finding the optimal call admission policy.

6 Conclusions

In this paper, we proposed a new classification of user based call admission policies in mobile cellular networks. The proposed classification not only provides a coherent framework for comparative studies of existing approaches, but also helps future researches and developments of new call admission policies.

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