Int J Wireless Inf Networks (2015) 22:53–66
DOI 10.1007/s10776-014-0255-7

Call Admission Control for Soft Handoff Coverage in CDMA Cellular System

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Received: 7 October 2013 / Accepted: 19 November 2014 / Published online: 30 November 2014

Abstract In code division multiple access mobile cellular networks, the transmission quality can be improved by using the soft handoff techniques. The present investigation is concerned with the admission control policies by exploiting the soft handoff coverage area of the cellular radio network. We suggest finite Markov models for the admission control based on reserve channel and sub-rating policies. In reserve channel policy, a fixed number of channels are reserved exclusively to serve the handoff calls whereas according to sub-rating policy, the occupied channels can be split into two half rate channels to accommodate more handoff voice calls. It is also considered that the new call generation rate per unit area is uniformly distributed over the service area. Various performance indices are derived in terms of steady state probabilities. For some special situations, we validate and compare the models developed with previous existing models by setting the system descriptors. To examine the effect of various parameters on the performance measures, the sensitivity analysis is carried out by taking illustrations.

Keywords Code division multiple access · Cellular system · Soft handoff · Handoff prioritization · Channel reservation · Sub-rating · Blocking

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1 Introduction

Cellular services based on 3rd generation (3G) technology are now being used by millions of people worldwide. The number of customers requiring multimedia services which include short messaging, voice, data and video, and many more, is increasing exponentially. The mobile radio industry has to evolve the current radio infrastructures in such way that it can accommodate the increasing demands of services in an efficient manner. Though many countries are yet to deploy 4th generation (4G) networks, the speculations of the market experts clearly indicate to a significant boom in this technology will be adopted by the end of year 2020.

In the past decade, it has been shown that code division multiple access (CDMA) is the most suitable multiple access technique for 3G systems. This technology has offered huge capacity over the time division multiple access (TDMA), frequency division multiple access (FDMA) and their combinations. CDMA has soft capacity in which all users can use the same frequencies at the same time while they are coded separated. Any single user adds gradually to the total interference in the system with no waste of time or frequency resources, thus enhancing the network capacity. The capacity reaches its maximum whenever the interference level in the cell reaches a certain level. At this level new users can be admitted in the system by degrading the quality of existing users below a certain acceptable limits by sub-rating the occupied channel into two channels.

Cellular networks are being extensively deployed and upgraded in order to cope up with the steady rise of user-traffic. This has created the need for new and robust analytical techniques to study the quality of user service. To study the performance of a wireless network supporting new/handoff data and voice calls, many researchers has proposed prioritised channel assignment schemes [1, 6, 12, 14, 20, 21, 27]. However, to handle the increasing number of users of multimedia services there is urgent need to design new call admission control policies which can also come up with the diverse traffic pattern and QoS requirements. In channel reservation scheme, a fixed number of channels can be reserved to give priority to the handoff calls. Sometime, more voice calls can be accommodated by dividing the busy reserve channel into two half rate channels, one to serve the existing call and the other one to serve the handoff request, the process is sub-rating [10]. The combination of channel reservation and sub-rating can be used to achieve the desired grade of services (GoS) [9, 11, 13].

Soft handoff is a key aspect of CDMA cellular systems. In CDMA mobile stations (MSs) inside soft handoff area utilizes multiple radio channels and receives their signal from multiple base stations (BSs) at the same time. It is worth-mentioning that less power is required on the forward and reverse links in a soft handoff process which results in the diversity gains as such the total system interference can be reduced. Earlier researches on soft handoff in CDMA have focused on the issues related to handoff delay versus cell coverage along with the wireless channels quality (Cho et al. [4], Avidor et al. [3], Ma et al. [16] and Roy and Kundu [18]). Anupama et al. [2] gave a comprehensive survey on the soft handoff prioritized schemes for CDMA systems. To support soft handoff calls with quality of service (QoS) assurances for both the uplink and downlink connections, a prioritized call admission control model in a CDMA system was studied by Chu et al. [5]. Tailselvan and Manivannan [24] analyzed the downlink performance of a wireless CDMA during soft handoff. The effect of including the soft handover in cell planning optimization was given by Ghosh et al. [7]. Saini and Gupta [19] presented a model to improve the capacity of soft handoff in wireless mobile communication using micro diversity.

In the recent past, the world has entered in 4G mobile communication where it enabled the users to access their favourite online content at a lightning fast speed, from anywhere they want. Even after the launch of 4G services, the 3G wireless/cellular communication is still dominating the global market place. The 4G technology, though offers better speed, its availability is still restricted to some developed countries whereas 2G/3G services are available almost at every nook and corner of the globe. Due to the lack of infrastructural resources, CDMA based mobile communication is still popular and prevalent. The trend of high speed integrated services on such mobile network has also grievance the congestion problem which is the key issue in the present scenario.

Much works on the traffic modeling of wireless mobile communication system in literature deals with infinite Markov process. However, a limited number of users can be allowed to have specific quality service based on prioritization. In this paper, to give priority to the soft handoff calls, guard channel policy is proposed for both finite capacity and finite population scenarios. In case when the traffic of new call is low in comparison to handoff voice call due to high mobility, the provision of sub-rating of guard channels is made to accommodate more voice calls. To tackle, different classes of traffic in finite capacity/population environment, we develop four Markov models (i) Finite capacity model with reserve channel (ii) Finite capacity model with subrating (iii) Finite population model with reserve channel and (iv) Finite population model with sub-rating. The impact of enlarging and shrinking the soft handoff coverage area on the new call blocking and handoff call dropping probabilities is also taken into consideration. The noble feature of enlarging and shrinking the soft handoff coverage area makes our models more realistic to deal with real time communication system in particular when voice traffic load is high. The admission control schemes are proposed based on varying handoff coverage area by developing the finite traffic models of individual and combination of guard channel and sub-rating channel assignment policy which were not available in the earlier existing literature. In special case when reserve channel scheme was not used to give the priority to handoff calls, the first model coincides with the model established by Sheu and Hou [22]. In today world as cellular users are increasing with exponential rate, it is very much essential to deal with this heavy congestion situation efficiently. The reserve channel scheme gives the better quality of service in comparison to without reserve channel scheme. The Model II of the present investigation supports more handoff voice calls by employing the sub-rating scheme, in comparison Model I. When there is a heavy traffic of handoff calls inside the network, the sub-rating scheme helps to lower down the blocking of the incoming handoff voice calls. When assumption of sub-rating scheme is relaxed, the Model II coincides with the models established by Kim and Sung [15] and Sheu and Hou [23]. Model III and Model IV were for finite population with reserve channel and subrating scheme, respectively. When the assumption of finite population and reserve channel are not taken into account, the Model III coincides with the model developed by Sheu and Hou [22]. Similarly, on omitting the three noble features i.e. the finite population, reserve channels provisioning and sub-rating, the Model IV is similar to the models established by Kim and Sung [15] and Sheu and Hou [23].

We have shown that using the reserve channel policy and subrating policy, the new call blocking probability and handoff call dropping probability can be reduced significantly. It is also realized that by shrinking the soft handoff region, one can reduce the new call blocking and handoff call dropping probabilities. This fact is validated by numerical simulation based on the analytical results established in our investigation. The rest of paper is organized as follows. Section 2 deals with the description of soft handoff model and traffic model along with the notations and formulae. Finite Markov models along with their respective performance measures are discussed in Sect. 3. Some special cases are deduced in Sect. 4 whereas the sensitivity analysis is carried out in Sect. 5. In Sect. 6, conclusions are drawn.

2 The Soft Handoff Model

Several mobile stations (MSs) in CDMA mobile cellular systems can be connected with multiple base stations (BSs) simultaneously using a soft handoff technique. The path diversity on the forward and reverse traffic channels is the key advantage of soft handoff technique. The soft handoff works on the principle of make before break. The pilot signal strength of BS that a mobile station (MS) can detect is inversely proportional to the distance between MS and BS. Figure 1 shows the soft handoff situation of a call. When the power received by the MS from the BS of a cell go beyond a predefined value T_{ADD}, a new link to the BS is established while the old link to the old BS is still retained. When the pilot signal strength from old BS as well as from new BS becomes less than the threshold value (T_{DROP}), then the weak (bad) connection is released.

In Fig. 2, we suppose that the service area is divided into hexagonal cells. For simplicity, the shape of the cells is approximated by a circle. Also, we assume that MSs are evenly distributed within service area. R is defined as the distance of hexagonal centre to any vertex Also, the equivalent radius of hexagonal cell is defined as R_{eq}. Cho et al. [4] established that the equivalent radius $R_{eq} \cong 0.91R$. Further, the circle with radius 'bR_{eq}' is considered as the inner cell whereas the circle with the radius 'aR_{eq}' is referred to as the outer cell. The hexagonal cell with radius R_{eq} is referred to as the original cell. For simplicity, the threshold T_{DROP} and T_{ADD} can be defined as the function of R_{eq}. Thus, $T_{DROP} = aR_{eq}$ and $T_{ADD} = bR_{eq}$ where $1 \leq a \leq 2$ and $0 \leq b \leq 1$.

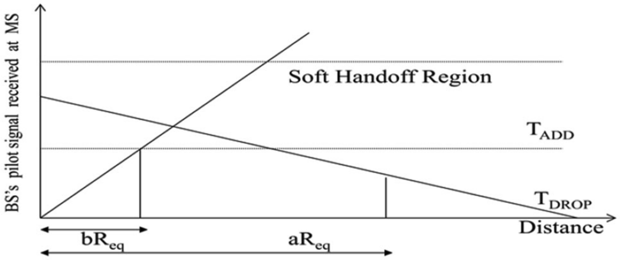


Fig. 1 Soft handoff situation in a CDMA cellular system

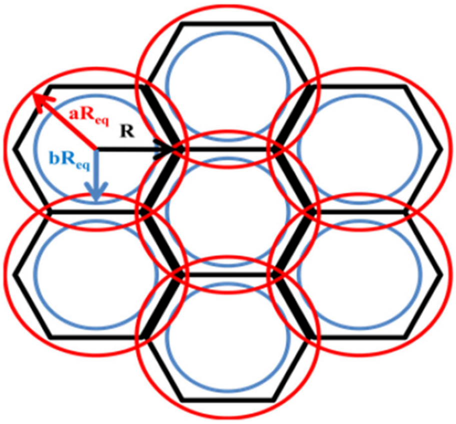


Fig. 2 Hexagonal cell structure and their soft handoff boundaries

At equilibrium, the average handoff rate of incoming traffic to a cell is equal to the average handoff rate of outgoing traffic to the cell [17]. The soft handoff rate in a cellular system can be defined as the frequency of the soft handoff attempts that a call makes before its termination. It can be determined based on many factors such as size and the shape of a cell, the call density and the moving speed of MS. The average outgoing handoff rate (λ) is obtained using [25]

$$\lambda = \frac{\rho V L}{\pi} \tag{1}$$

where ρ, V and L are the call density per unit area, the average moving speed of MS and the perimeter of the cell area, respectively. Equation (1) is known as Thomas's formula.

2.1 Traffic Model

The cell coverage in a CDMA cellular system is defined as the maximum distance that a given user of interest has from the base station and is still receiving reliable received signal strength at the base station. The coverage of a cell has an inverse relationship with the user capacity of the cell [26]. An increase in the number of active users in the cell there is an increment in the total interference, seen at the receiver's end. This causes an increase in the required received power for each user. This is due to the fact that each user has to maintain a certain signal-to-interference ratio (SIR) at the receiver for the satisfactory performance. We consider a cluster of K hexagonal cells of uniform system in a cellular network (see Fig. 2). The traffic in the network is supposed to consists of two types of calls i.e. data and voice calls. In reality the mobile call generations are not uniformly distributed over a service area. Also the speed and the direction of a call may vary according to its call duration. For the sake of analytical tractability, we make some assumptions. The speed and the direction of mobile calls are uniformly distributed in the interval [0, V_{max}] and [0, 2π], respectively. We also assume that new calls are generated according to Poisson process with mean rate λ_a per unit area. During the call interval, the speed and the direction of a generated mobile call will remain unchanged. Let T_{cd} be a random variable for the call duration time and is assumed to be exponentially distributed with mean 1/μ. The probability density function of T_{cd} is expressed as

$$f_{T_{cd}}(t) = \begin{cases} \mu e^{-\mu t}, & t \geq 0 \\ 0, & otherwise \end{cases} \tag{2}$$

When a call is generated in an original cell, it is referred as a new call. When all the channels in an original cell are busy, the new call moves to soft handoff region. This handoff region lies between the inner cell and outer cell. The new call selects new BS within this region based on the strongest strength of pilot signals. This situation is known as handoff. If the selected new BS can offer a free channel to the mobile call, we say that the handoff is successful. Once the handoff process is successful, the old link to the old BS is disconnected and the new link to the new BS is connected.

2.2 Notations and Some Results

The average blocking probabilities of new call and the average dropping probabilities of the handoff calls are the two important performance indices of our interest. As shown in Fig. 2, we assume that the entire cells are identical in shape and the channel distribution is also identical. Thus, the new call generation rate per cell (λ_n) is given by

$$\lambda_n = \lambda_a A_o = \lambda_a \pi R_{eq}^2 \tag{3}$$

where A_o is the area of the original cell and λ_a is the new call generation rate per unit area.

There are two possibilities when the handoff voice (handoff data) attempts may occur:

(I) In this case, we consider the mobile calls are directly degenerated in the overlapping area of the two neighboring cell i.e. the soft handoff region. The new call generation rate is uniformly distributed over this overlap area. All the new call generated in the overlap area may not be passed over to the neighboring cell; rather only half of them are likely to be handoff voice (handoff data) attempts to other neighboring cells. Let the handoff voice (handoff data) attempts rate be denoted by $\lambda_{hv1}(\lambda_{hd1})$, and $\lambda_{h1} = \lambda_{hd1} + \lambda_{hv1}$ be the total handoff attempts rate and is given as

$$\lambda_{h1} = \frac{1}{2}\pi\lambda_a(a^2 - b^2)R_{eq}^2(1 - P_B) \tag{4}$$

where P_B is the blocking probability of new calls.

(II) Here, we consider that the mobile calls are generated in the inner cell. In this situation, when a mobile call crosses the inner cell boundary and entered in the soft handoff region, the handoff process occurs. Let $\lambda_{hv2}\,(\lambda_{hd2})$ be the handoff voice (handoff data) attempt rate and $\lambda_{h2} = \lambda_{hd2} + \lambda_{hv2}$ be the total handoff attempts rate for case (II). In this case, Thomas formula [25] yields $\lambda = \frac{\rho \bar{V} L}{\pi}$, where $\lambda = \lambda_{h2}$, $L = 2\pi b R_{eq}$ and $\overline{V}$ is the speed of mobile calls.

Thus, the overall handoff attempt rate is given by

$$\lambda_h = \lambda_{h1} + \lambda_{h2} \tag{5}$$

The call density per unit area is denoted as ρ and is obtained using

$$\rho = \left(\frac{\lambda_{nc} + \lambda_{hc}}{\mu}\right)\frac{1}{A_o} \tag{6}$$

where λ_{nc} is the successful generation rate of the new calls, λ_{hc} is the successful handoff attempt rate of the handoff calls, $\frac{1}{\mu}$ is the mean channel holding time, A_o is the area of outer cell.

Thus, we obtain

$$\lambda_{nc} = (1 - P_B)\,\lambda_n \tag{7}$$

$$\lambda_{hc} = (1 - P_f)\,\lambda_h \tag{8}$$

$$A_o = \pi(aR_{eq})^2 \tag{9}$$

where P_B and P_f are the blocking probabilities of new calls and failure probability of handoff calls, respectively.

The occupied channel is said to be released only, if a call is terminated within a cell or it crosses the boundary of the outer cell or we can say it is not in of the coverage area of the cell. Let T_{ch} be the random variable for the channel holding time and can be expressed as

$$T_{ch} = \min(T_{cd},\ T_{ot}) \tag{10}$$

where T_{cd} and T_{ot} are the random variables for call duration time and call residual time, respectively. T_{cd} and T_{ot} both are assumed to be exponentially distributed with mean 1/μ and $1/\mu_{ot}$, respectively. The mean channel holding time is

$$\frac{1}{\mu_{ch}} = \frac{1}{\mu_{ot} + \mu} \tag{11}$$

We assume that the call residual time is directly proportional to the radius of outer cell. Thus the mean all residual time within the outer cell is given as [8].

$$\frac{1}{\mu_{ot}} = \frac{1}{\mu_o} x\, a \tag{12}$$

where $\frac{1}{\mu_o}$ is the mean residual time in the original cell. Now using Eqs. (11) and (12), we get

$$\frac{1}{\mu} = \frac{a}{a\mu_{cd} + \mu_o} \tag{13}$$

Since $1/\mu_o$ is inversely proportional to the speed of the mobile calls, the mean residual time in the original cell is given as

$$\frac{1}{\mu_o} = \frac{R_{eq}}{\bar{V}} \tag{14}$$

3 Markov Models

In this section, we develop Markov models for finite capacity and finite population with reserve channel scheme and sub-rating. The steady state probabilities of the system states, blocking probability of new calls and dropping probability of handoff calls are established for each scheme. The state transition diagrams for the Models I–IV are shown in Figs. 3, 4, 5, and 6, respectively.

3.1 Model I: Finite Capacity Model with Reserve Channel

In cellular radio system it is important to give priority to the ongoing calls in comparison to new calls. In this model, r channels among the total C channels are reserved for serving the handoff calls only. The remaining C-r channels serve both new and handoff calls. The state transition diagram depicting the in-flow and out-flow rates is shown in Fig. 3. The steady state probabilities for the scheme are obtained by using the product form solution (see Appendix 1) and is given by

$$P_j = \begin{cases} \dfrac{1}{j!}\left(\dfrac{\lambda_n + \lambda_h}{\mu}\right)^j P_0, & 1 \le j \le C - r \\ (\lambda_n + \lambda_h)^r \dfrac{(\lambda_h)^{j-(C-r)}}{j!\mu^j} P_0, & C - r + 1 \le j \le C \end{cases} \tag{15}$$

where

$$P_0 = \left[\sum_{j=0}^{C-r} \frac{1}{j!}\left(\frac{\lambda_n + \lambda_h}{\mu}\right)^j + \sum_{j=C-r+1}^{C} (\lambda_n + \lambda_h)^r \frac{(\lambda_h)^{j-(C-r)}}{j!\mu^j}\right]^{-1} \tag{16}$$

Thus, the average blocking probability of new calls (P_B) is given as

$$P_B = \sum_{j=C-r}^{C} P_j \tag{17}$$

When the handoff attempt occurs at the boundary of the outer cell and it could not get any channel from the neighboring cell, the handoff call will be dropped. Using Eq. (1) and the average failure probability of handoff calls (P_f), we can derive the average dropping rate of the handoff calls as

$$R_{Dh} = \frac{\rho \bar{V} L_0 P_f}{\pi} \tag{18}$$

where L_o is the perimeter of the outer cell, $\bar{V}$ is the speed of mobile calls and the average failure probability (P_f) of handoff calls is determined using

$$P_f = P_C \tag{19}$$

The average dropping probability of handoff calls is the ratio of the average dropping rate of the handoff calls (R_{Dh}) and the overall handoff attempt rate (λ_h). Thus, we have

$$P_{Dh} = \frac{R_{Dh}}{\lambda_h} = \frac{\rho \bar{V} L_0 P_f}{\pi \lambda_h} \tag{20}$$

3.2 Model II: Finite Capacity Model with Subrating

The previous scheme can be further improved by increasing its capacity to serve more handoff voice attempts. For this purpose sub-rating scheme is used in which reserve channels are split into two half rate channels to serve more handoff voice attempts. The state transition diagram for this model is shown in Fig. 4. The steady state probabilities

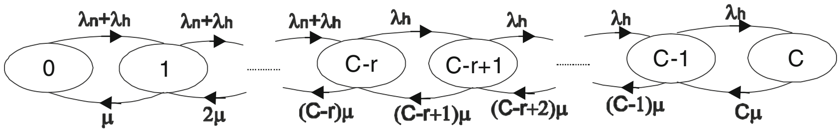


Fig. 3 State transition diagram for finite capacity model with reserve channel

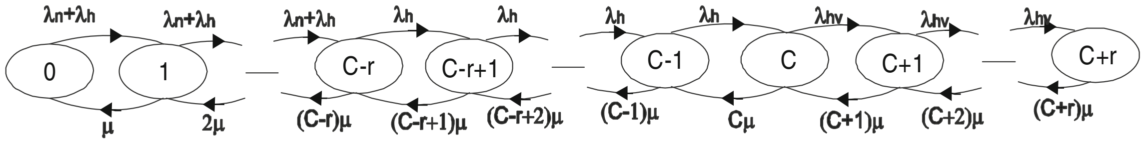


Fig. 4 State transition diagram for finite capacity model with subrating

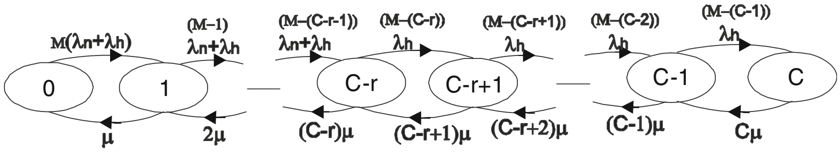


Fig. 5 State transition diagram for finite population model with reserve channel

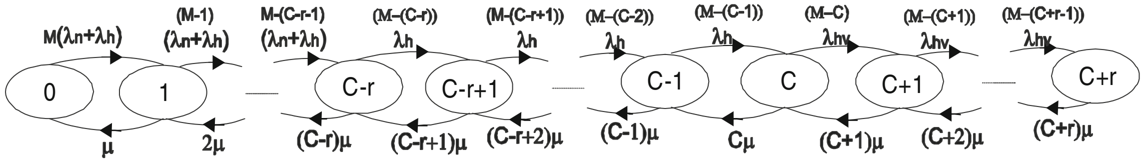


Fig. 6 State transition diagram for finite population model with subrating

for this model can be obtained using the product type solution (see Appendix 1) and is given by

$$P_j = \begin{cases} \frac{1}{j!}\left(\frac{\lambda_n + \lambda_h}{\mu}\right)^j P_0, & 1 \le j \le C - r \\ (\lambda_n + \lambda_h)^r \frac{(\lambda_h)^{j-(C-r)}}{j!\mu^j} P_0, & C - r + 1 \le j \le C \\ (\lambda_n + \lambda_h)^r \frac{(\lambda_h)^{(C-r)} (\lambda_{hv})^{(j-C)}}{j!\mu^j} P_0, & C + 1 \le j \le C + r \end{cases} \tag{21}$$

where

$$P_0^{-1} = \left[\sum_{j=0}^{C-r} \frac{1}{j!}\left(\frac{\lambda_n + \lambda_h}{\mu}\right)^j + \sum_{j=C-r+1}^{C} (\lambda_n + \lambda_h)^r \frac{(\lambda_h)^{j-(C-r)}}{j!\mu^j} + \sum_{j=c+1}^{C+r} (\lambda_n + \lambda_h)^r \frac{(\lambda_h)^{(C-r)} (\lambda_{hv})^{(j-C)}}{j!\mu^j} \right] \tag{22}$$

The average blocking probability of new calls (P_B) for this scheme is given as

$$P_B = \sum_{j=C-r}^{C+r} P_j \tag{23}$$

The average dropping probability of handoff data calls (P_{Dhd}) is given by

$$P_{Dhd} = \sum_{j=C}^{C+r} P_j \tag{24}$$

Similarly, as in the previous scheme, the dropping probability of handoff voice attempts is obtained by taking the average dropping rate of the handoff voice calls (R_{Dhv}) and the overall handoff attempt rate (λ_h) as given below

$$P_{Dhv} = \frac{R_{Dhv}}{\lambda_h} = \frac{\rho \bar{V} L_0 P_f}{\pi \lambda_h}, \tag{25}$$

where $P_f = P_{C+r}$.

3.3 Model III: Finite Population Model with Reserve Channel

In this scheme the incoming calls are originating from the finite population. The other features are similar to Model I. The state transition diagram for this model is shown in Fig. 5. Following the product type solution procedure, we obtain the steady state probabilities for this model as

$$P_j = \begin{cases} \binom{M}{j} \left(\frac{\lambda_n + \lambda_h}{\mu}\right)^j P_0, & 1 \le j \le C - r \\ \binom{M}{j} (\lambda_n + \lambda_h)^r \frac{(\lambda_h)^{j-(C-r)}}{\mu^j} P_0, & C - r + 1 \le j \le C \end{cases} \tag{26}$$

where

$$P_0^{-1} = \left[\sum_{j=0}^{C-r}\binom{M}{j}\left(\frac{\lambda_n+\lambda_h}{\mu}\right)^j + \sum_{j=s+1}^{C}\binom{M}{j}\cdot (\lambda_n+\lambda_h)^r\frac{(\lambda_h)^{j-(C-r)}}{\mu^j}\right] \tag{27}$$

The average blocking probability of new calls (P_B) and the average dropping probability of handoff calls (P_{Dh}) are obtained using Eqs. (17) and (20), respectively.

3.4 Mode IV: Finite Population Model with Subrating

The state transition diagram for this model is shown in Fig. 6. This model is similar to Model II; the only difference is that the incoming calls are originating from finite. The steady sate probabilities for this case are obtained using product type solutions as

$$P_j = \begin{cases} \binom{M}{j}\left(\frac{\lambda_n+\lambda_h}{\mu}\right)^j P_0, & 1 \le j \le C-r \\ \binom{M}{j}(\lambda_n+\lambda_h)^r\frac{(\lambda_h)^{j-(C-r)}}{\mu^j}P_0, & C-r+1 \le j \le C \\ \binom{M}{j}(\lambda_n+\lambda_h)^r\frac{(\lambda_h)^{(C-r)}(\lambda_{hv})^{(j-C)}}{\mu^j}P_0, & C-r+1 \le j \le C \end{cases} \tag{28}$$

where

$$P_0^{-1} = \left[\sum_{j=0}^{C-r}\binom{M}{j}\left(\frac{\lambda_n+\lambda_h}{\mu}\right)^j + \sum_{j=C-r+1}^{C}\binom{M}{j}(\lambda_n+\lambda_h)^r\frac{(\lambda_h)^{j-(C-r)}}{\mu^j} + \sum_{j=c+1}^{C+r}\binom{M}{j}(\lambda_n+\lambda_h)^r\frac{(\lambda_h)^{(C-r)}(\lambda_{hv})^{(j-C)}}{\mu^j}\right] \tag{29}$$

The average blocking probability of new calls (P_B), the average dropping probability of handoff data calls (P_{Dhd}) and the average dropping probability of handoff voice attempts (P_{Dhv}) are obtained by using Eqs. (23), (24) and (25), respectively.

4 Special Cases

In this section, in order to validate the analytical results derived in the previous section with some existing models, we deduce some special cases by assigning the appropriate values of the parameters as follows:

(i) *Case I* Finite capacity and infinite population model without reserve channel

If the handoff priority scheme (reserve channel scheme) is not taken into consideration i.e. on substituting the value of reserve channel (r) is equal to zero, in Eqs. (15) and (16), our Model I coincides with the model developed by Sheu and Hou [22].

(ii) *Case II* Finite capacity and infinite population model without reserve channel

When the population size is infinite and reserve channels are unavailable in the network i.e. on assigning the values of M = 1 and r = 0 in Eqs. (26) and (27), the Model III matches with the model described in Sheu and Hou [22].

(iii) *Case III* Finite capacity model with reserve channel but without sub-rating

When the admission of the incoming calls inside the network is controlled without using the sub-rating scheme i.e. only reserve channel scheme is present to give the priority to the oncoming handoff calls, the Model II coincides with the model developed by Kim and Sung [15] and Sheu and Hou [23]. In other words on equating $P_j = 0$ for $C+1 \le j \le C+r$ in Eqs. (21) and (22); the reduced expressions for our Model II match with the expressions given in Kim and Sung [15] and Sheu and Hou [23].

(iv) *Case IV* Finite capacity and infinite population model with reserve channel but without sub-rating

Bearing in mind that the subrating scheme is not used i.e. only reserve channel handoff priority scheme is taken into consideration and also the calling population size is infinite [i.e. on assigning the values of M = 1 and equating $P_j = 0$ for $C+1 \le j \le C+r$ in Eqs. (28) and (29)]; the results for Model IV coincide with the results established in Kim and Sung [15] and Sheu and Hou [23].

With the above discussion, it is clear that our models are more general and robust in comparison to the previously existing models. The proposed reserve channel and subrating schemes can handle the congestion situation more efficiently and may be helpful in reducing the blocking and dropping of incoming calls significantly.

5 Sensitivity Analysis

To predict the performance of CDMA cellular network and to validate the tractability of the analytical results established in Sect. 3, the sensitivity analysis is performed in this section. The numerical results for blocking probabilities of new calls and dropping probabilities of handoff calls mentioned in Sect. 3, are calculated by using product type technique (see Appendix 1). In the present section, the coding of product type formulae was done by developing a program using MATLAB software. For illustration

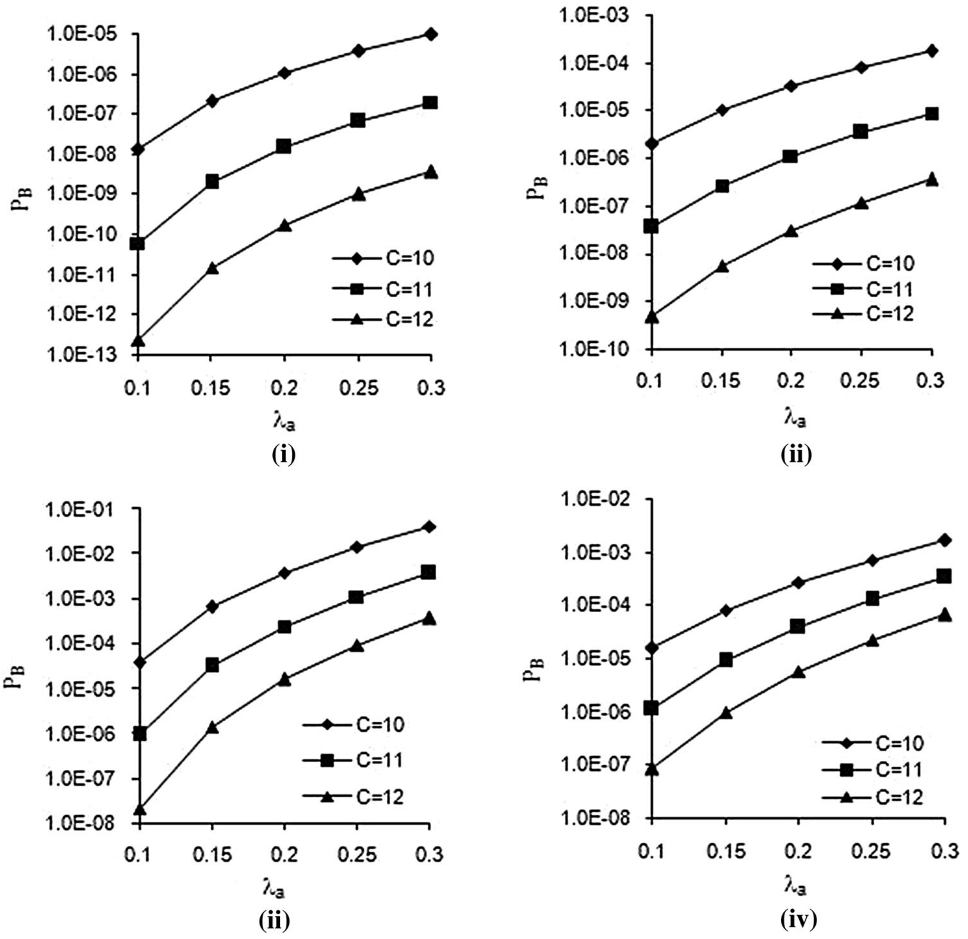


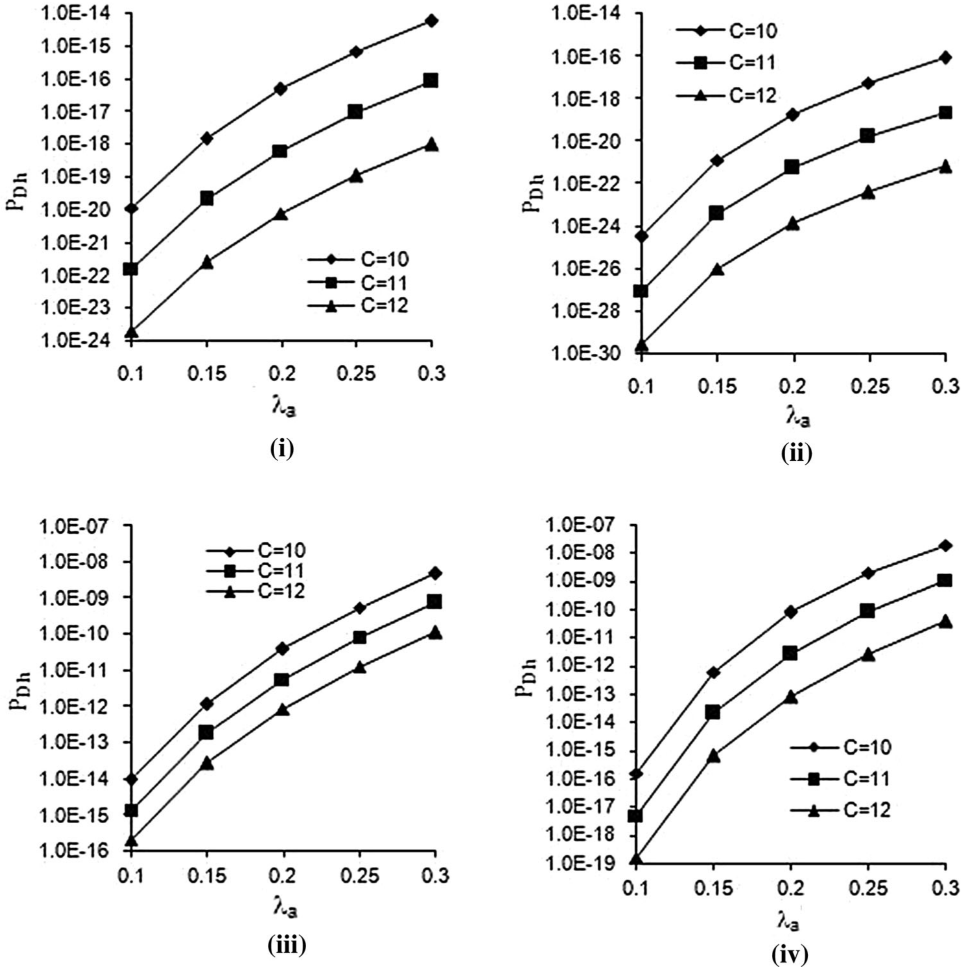
Fig. 7 Average blocking probability of new calls vs 'λ_a' for different values of 'C' for **i** Model I, **ii** Model II, **iii** Model III, **iv** Model IV

purpose, we set default parameters as $C = 10$, $M = 5$, $r = 4$, $a = 1.2$, $b = 0.8$, $\lambda_a = 0.1$ and $\overline{V} = 30$ km/h. The effect of enlarging and shrinking the soft handoff region on blocking probabilities are also examined by graphical representation shown in Figs. 7, 8, 9, 10 11, 12, 13, 14, and 15.

Figures 7i–iv and 8i–iv show the results for the average blocking probability of new calls (P_B) and average dropping probability of handoff calls (P_{Dh}) by varying new call generation rate (λ_a) for different values of number of channels (C) in a cell for Model I–IV, respectively. We set the default parameters for Figs. 7 and 8 as $M = 5$, $r = 4$, $a = 1.2$, $b = 0.8$ and $\overline{V} = 30$ km/h. In Figs. 7i–iv and 8i–iv, P_B and P_{Dh} increase sharply as λ_a increases. This effect of new call generation rate on P_B and P_{Dh} is as per our expectation for any mobile cellular network as with the increasing generation rate of the incoming traffic, the blocking probability of new calls and dropping probability of handoff calls in the network increase significantly. It is also seen in Figs. 7i–iv and 8i–iv that P_B and P_{Dh}, respectively decrease on increasing the value of C. This can be physically explained as by providing the service to the incoming calls at faster rate, the blocking and dropping probabilities reduce significantly.

It is clear from the Fig. 7i, ii that P_B remains almost constant as increment is of order 10^{-13} to 10^{-11}. The constant trend of P_B in Fig. 7ii is due to the sub-rating policy for handoff voice calls which further results in increase in the blocking probability of new calls in comparison to Fig. 7i. The similar trend of blocking probability of new calls is seen in Fig. 7iii, iv, for MODELs III and IV which dealt with finite population traffic. In Fig. 7iii, iv, we notice that P_B also increases very slowly.

From Fig. 8i, ii, we observe the flat curves which is due to fact that the decreasing trend of dropping probability of handoff calls is of order 10^{-24} to 10^{-30}. This pattern of P_{Dh} is also because of the use of sub-rating scheme. The subrating scheme is used along with the reserve channel scheme in Model II for which graphs are plotted in Fig. 8ii. We notice a reduction in the dropping of the handoff calls. Similarly, for finite population Models III and IV, the decreasing trend in P_{Dh}, is quite remarkable as can be observed in Fig. 8iii, iv.



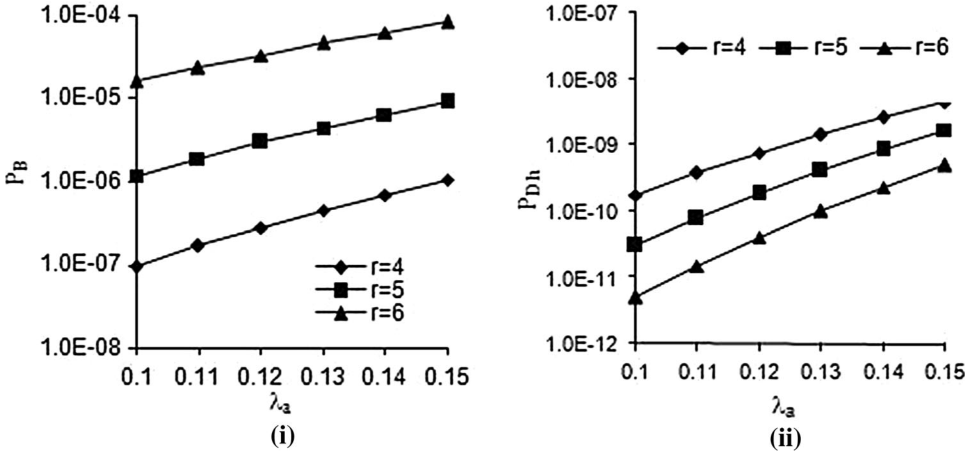
(i)

(ii)

(iii)

(iv)

Fig. 8 Average dropping probability of handoff calls vs 'λ_a' for different value of 'C' for **i** Model I, **ii** Model II, **iii** Model III, **iv** Model IV



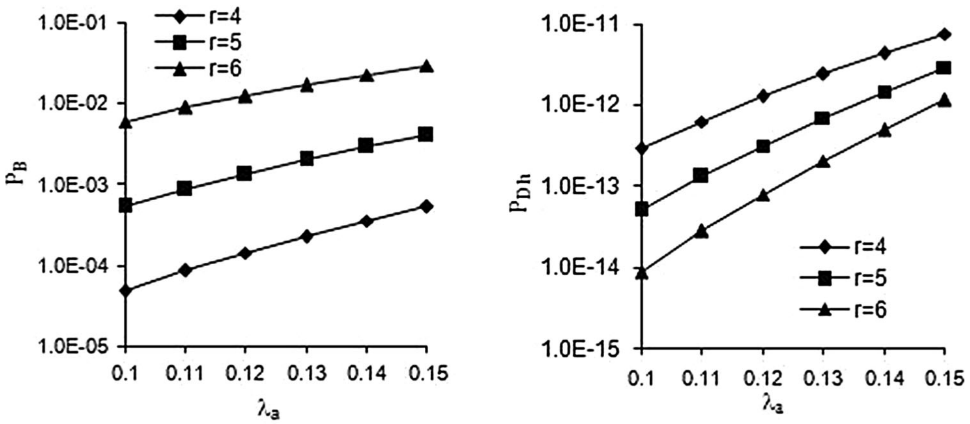
(i)

(ii)

Fig. 9 Effect of 'r' and 'λ_a' on the **i** average blocking probability of new calls, **ii** average dropping probability of handoff calls, for Model I

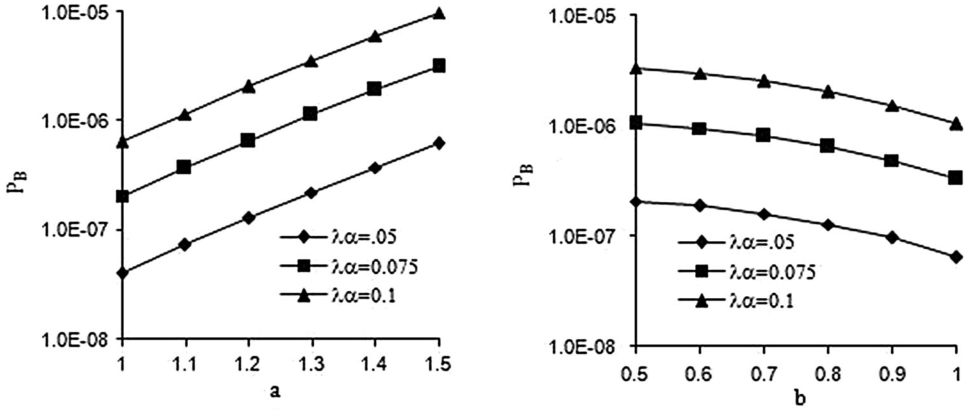
Figure 9i, ii exhibit the trends for the average blocking probability of new calls (P_B) and dropping probability of handoff calls (P_{Dh}), respectively by varying new call generation rate (λ_a) for different number of reserve channels (r) for finite capacity model with reserve channel (i.e. Model I). The default parameter for Fig. 9 are set as $C = 10$, $a = 1.2$, $b = 0.8$ and $\overline{V} = 30$ km/h. In Fig. 9i, ii, both P_B and P_{Dh} increase first slowly then sharply as λ_a increases, which is quite remarkable. In Fig. 9i we observe that P_B increases sharply as the number of reserve channel

Fig. 10 Effect of ‘r’ and ‘λ_a’ on the **i** average blocking probability of new calls, **ii** average dropping probability of handoff calls, for Model II



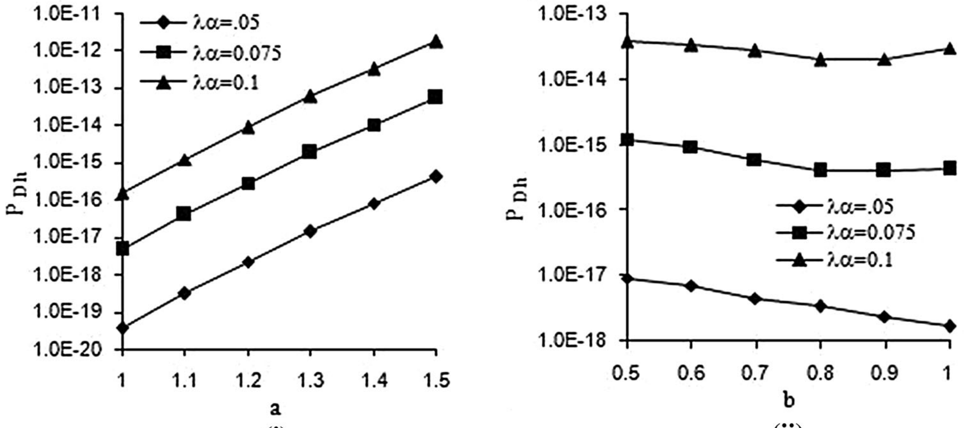
(i) (ii)

Fig. 11 Effect of ‘λ_a’ on average blocking probability of new calls for Model III by varying **i** ‘a’, **ii** ‘b’



(i) (ii)

Fig. 12 Effect of ‘λ_a’ on the average dropping probability of handoff calls for Model III by varying **i** ‘a’, **ii** ‘b’



(i) (ii)

(r) increases. This effect of ‘r’ on P_B is quite reasonable as reserve channels only support the handoff calls which results in a significant increment in P_B. The reverse trend with respect to ‘r’ is found in Fig. 9ii i.e. P_{Dh} decreases as ‘r’ increases, which is same as per our expectation. It is seen that by employing the reserve channel scheme, the dropping of handoff calls can reduce to a good extent.

Figure 10i, ii display the graphs for average blocking probability of new calls (P_B) and dropping probability of handoff calls (P_{Dh}), respectively by varying new call

Fig. 13 Effect of ‘λ_a’ on average blocking probability of new calls for Model IV by varying **i** ‘a’, **ii** ‘b’

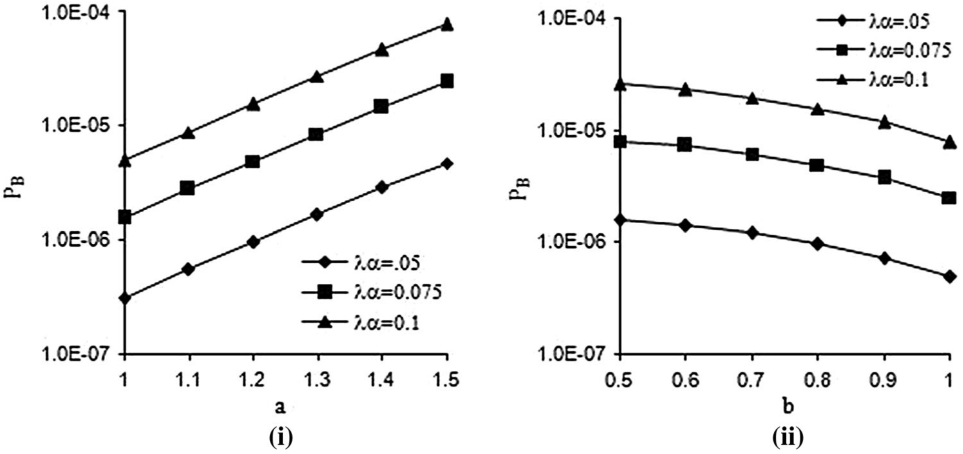


Fig. 14 Effect of ‘λ_a’ on average blocking probability of new calls for Model IV by varying **i** ‘a’, **ii** ‘b’

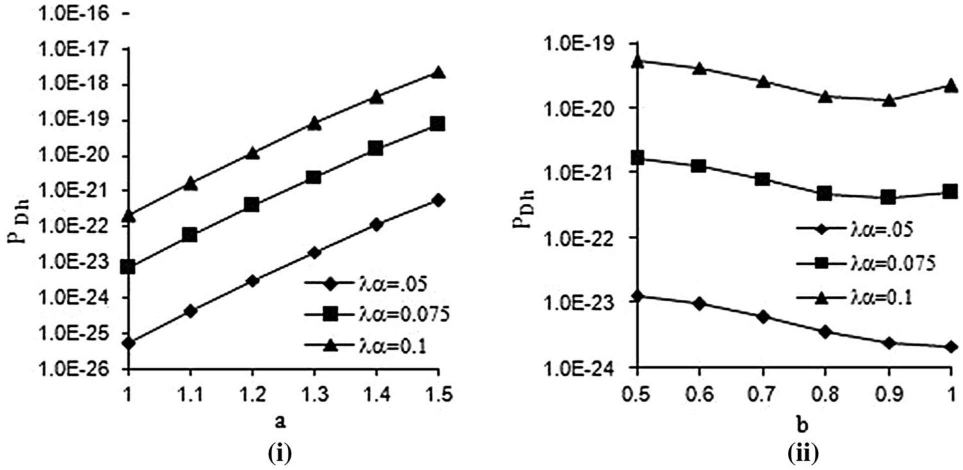
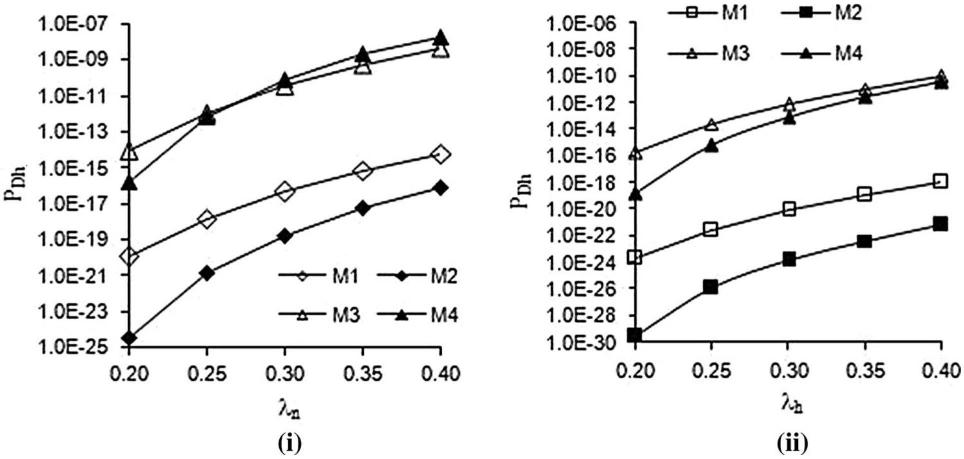


Fig. 15 Comparison of average dropping probability of handoff calls for Model I, Model II, Model III and Model IV



generation rate (λ_a) for different values of reserve channels (r) for finite capacity model with sub-rating Model II). The default parameter for Fig. 10 are chosen as $C = 10$, $M = 5$, $a = 1.2$, $b = 0.8$ and $\overline{V} = 30$ km/h. By varying λ_a for different values of ‘r’, Fig. 10i, ii show the similar trend of P_B and P_{Dh} as seen in Fig. 9i, ii. On comparing Figs. 9i and 10i, we notice that P_B increases; this is due to the use of sub-rating scheme. Similarly, on comparing Figs. 9ii and 10ii, it is seen that P_{Dh} decreases. Again, this effect is because of the sub-rating policy which is used for handoff calls. The patterns of both the figures are quite close to real life situation.

We know that a and b represent the soft handoff region between the outer and the inner cell, respectively. Figures 11i, ii and 12i, ii depict the graphs for P_B and P_{Dh} by varying parameter a and parameter b for different values of 'λ_a', respectively for Model III (finite population model with reserve channel). The default parameters for Figs. 11, 12, 13, and 14 are set as $C = 10$, $M = 5$, $r = 4$ and $\overline{V} = 30$ km/h. In Figs. 11i and 12i, we increase the parameter a from 1.0 to 1.5 and observe three different settings of the new call generation rate per unit area (i.e. $\lambda_a = 0.05$, 0.075 and 0.1). For both the Figs. 11i and 12i, we fix the parameter $b = 0.8$. Since increment in parameter a will enlarge the soft handoff area, thereby the new call generation rate per cell (λ_a) will also increases accordingly. As observed from these two figures, a slight increase in λ_a can significantly increases the average blocking probability of new calls (P_B) and the average dropping probability of handoff calls (P_{Dh}) as depicted in Figs. 11i and 12i, respectively. Furthermore, we observe that P_B and P_{Dh} both increase as we increase the parameter a.

Figures 11ii and 13ii show the trends of P_B and P_{Dh} respectively, when the parameter b is increased from 0.5 to 1.0. Here, we fixed parameter $a = 2.1$. Since by increasing the parameter b, the soft handoff area reduces, we notice that the number of handoff attempts within that area becomes less. Consequently, both P_B and P_{Dh} are moderately decrease with the increase in parameter b. However, in Fig. 12ii we observe that when λ_a and parameter b attain higher values i.e. $\lambda_a = 0.1$ and as parameter b increases from 0.9 to 1.0, P_{Dh} starts increasing very slowly. This is due to the fact that by increasing the parameter b, the soft handoff region reduces which results in the increase in the number of new calls per cell. Thereby, the number of mobile calls competing for a fixed number of channels is increased. Therefore, as shown in Fig. 12ii, the curve of handoff call dropping probability (when $\lambda_a = 0.1$) first goes down smoothly and then goes up, as the parameter b is increased from 0.5 to 1.0.

Figures 13i, ii and 14i, ii exhibit the patterns of P_B and P_{Dh} by varying parameters a and b for different values of 'λ_a', respectively for Model IV (finite population model with sub-rating). In Figs. 13i and 14i, P_B and P_{Dh} increase by increasing 'λ_a' as well as parameter a, respectively. The observed trends for both Figs. 13i and 14i are same as noticed for Figs. 11i and 12i, respectively. Here, we notice that P_B increases in Fig. 13i in comparison to Fig. 11i; this increasing trend is due to implementation of sub-rating policy which is used in Model IV for handoff voice calls. The sub-rating policy further increases the blocking probability of new calls as shown in Fig. 13i. In Fig. 13ii, P_B increases with 'λ_a' whereas decreases by increasing parameter b. The trend of Fig. 13ii matches with the trend of graphs shown in Fig. 11ii. On comparing the Figs. 11ii and 13ii, we see that P_{Dh} decreases significantly in Fig. 13ii in comparison to Fig. 11ii. This decreasing trend of P_{Dh} is because of the sub-rating policy, which reduces the P_{Dh} to reasonably good extent in Fig. 13ii. Similarly the pattern depicted in Fig. 14ii is same as noticed in Fig. 12ii; here P_{Dh} decreases quickly (for Fig. 14ii) in comparison to that shown in Fig. 12ii.

The comparison of four Markov models is made by plotting the graph of average dropping probability of handoff calls (P_{Dh}) in Fig. 15i, ii by varying arrival rates. It is noticed that P_{Dh} for finite capacity model with reserve channel (Model I) and finite capacity model with sub-rating channel (Model II) are lesser than that of finite population model (Model III) with reserve channel and finite population model with subrating channel (Model IV). It is observed that the dropping probability of handoff calls is further reduced with respect to handoff calls (λ_h) in comparison to arrival rate of new calls (λ_n). We can also see that the dropping probabilities give better results for the Model II and Model IV in comparison to Model I and Model III. This is due to the implementation of sub-rating scheme, which helps in reduction in the dropping of handoff voice calls; both of these figures demonstrate that how the arrival rates significantly affect the dropping of handoff calls but new call blocking probability seems to slightly increase in heavy traffic case. If we compare Model II and Model IV, Model IV seems to less effective; the reason behind this can be attributed to finite calling population.

Overall we conclude that P_B and P_{Dh} increase as 'λ_a' increases. P_B increases when we increase the values of 'r' whereas P_{Dh} decreases as 'r' increases; this is due of provision of reserve channels to support only handoff calls. Also, by the enlarging the soft handoff area, the blocking and dropping probabilities of calls increase significantly while reduction in the soft handoff area can decrease the both blocking and dropping probabilities considerably.

6 Conclusion

In this paper, we have developed four Markov models to study the influence of enlarging or shrinking the soft handoff coverage on the new call blocking and the handoff call dropping probabilities in a CDMA cellular radio network. It is demonstrated that the enlarging the soft handoff region may significantly increase the new call blocking and the handoff call dropping probabilities, while shrinking the soft handoff region can reduce these two probabilities slightly. By assuming the new call generation rate per unit area small and on reserving 40 % of channels from the total available channels for handoff calls, we have shown that the handoff call dropping probability can reduce significantly for both finite capacity and finite population models. It has been demonstrated that sub-rating policy is helpful in accommodating more handoff voice calls in the network, however new call blocking probability increases very less for both finite capacity and finite population models. Also, whenever the traffic load of new and handoff call is high, performance of the network seems to improve by reducing the soft handoff region.

The key advantage of the soft handoff technology can be attributed to the fact that there is no change in frequency or timing as a user passes from one base station to another. A soft handoff process is mainly suitable for managing voice call efficiently in cellular networks and latency sensitive communication services such as videoconferencing based on CDMA or GSM technology. The quantitative tradeoffs between numerous advantages and disadvantages of soft handoff require to be further investigated. The future research can be easily carried out by extending the analytical results established in this study in view of 4G networks by taking the concepts of reserve channels, sub-rating and varying handoff over lapping area into consideration.

Acknowledgments We are thankful to Professor G. C. Sharma, Dr. B. R. A. University, Agra for his advice and to the Chief Editor and learned reviewers for their valuable suggestions and comments for the improvement of the paper.

Appendix 1

Product type solution

Using the appropriate transition rate and with the help of the state transition diagram i.e. Fig. 3, the following set of equations is constructed.

$$-(\lambda_n + \lambda_h)P_0 + \mu P_1 = 0 \tag{30}$$

$$(\lambda_n + \lambda_h)P_{j-1} - (\lambda_n + \lambda_h + j\mu)P_j + \mu(j+1)P_{j+1} = 0, \quad 1 \le j \le C - r - 1 \tag{31}$$

$$(\lambda_n + \lambda_h)P_{C-r-1} - (\lambda_n + \lambda_h + (C-r)\mu)P_{C-r} + \mu(C-r+1)P_{C-r+1} = 0 \tag{32}$$

$$\lambda_h P_{j-1} - (\lambda_h + j\mu)P_j + \mu(j+1)P_{j+1} = 0,\ C - r + 1 \le j \le C - 1 \tag{33}$$

$$\lambda_h P_{C-1} - C\mu P_C = 0 \tag{34}$$

Equation (30) can be written as

$$P_1 = \frac{(\lambda_n + \lambda_h)}{\mu} P_0 \tag{35}$$

Solving Eqs. (31) and (32) recursively, we obtain product type result given in Eq. (15) for the interval $1 \le j \le C - r$.

Similarly, on solving Eqs. (33) and (34) recursively, we get the product type result as given in Eq. (15) for the range $C - r + 1 \le j \le C$.

Now, on applying the normalizing condition i.e. $\sum_{j=0}^{C} P_j = 1$, we obtain Eq. (16).

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