Combined Guard Channel and Mobile Assisted Handoff for Cellular Networks

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***Abstract*— For cellular communication systems, mobility and limited radio coverage of a cell require calls to be handed over from one base station system (BSS) to an another BSS. Due to the limited bandwidth available in various cells, there is a finite probability that an ongoing call while being handed off may get dropped. Minimizing the dropping of ongoing calls during handoff is an important design criterion. Some digital cellular systems, $e.g.$, the GSM and the IS-136 use the mobile assisted hand off (MAHO) in which a mobile terminal (MT) assists its BSS and mobile switching center (MSC) in making handoff decisions. MAHO requires an MT to regularly report back to its serving BSS, its current radio-link state (defined in terms of the received signal strength indicator (RSSI) and the bit error rate (BER)) of transmissions received from the neighboring BSSs. Some researchers have suggested that a base station needs to give priority to the handoff calls over the new calls. This requires each cell to reserve a number of guard channels (GCs) to be used exclusively for processing the handoff calls. Since MAHO makes handoff decisions based solely on RSSI/BER measurements, there is a finite probability that some handoff calls may get dropped due to the non-availability of free channels in the neighboring cell that is being handed off the call. Conversely, if a handoff decision is based solely on the availability of a free channel without regard to the signal quality, it may also result in some of the handed off calls being dropped due to poor signal quality. In this paper, we propose a new handoff technique by combining the MAHO and GC techniques. In the proposed technique, the MT reports back not only the RSSI and the BER, but also the number of free channels available for the handoff traffic. This will ensure that a handed off call has acceptable signal quality as well as a free available channel. The performance of this handoff technique is analyzed using an analytical model whose solution gives the desired performance measures in terms of blocking and dropping probabilities.**

***Index Terms*— Cellular communications, Wireless, Handoff, Markov chains**

I. INTRODUCTION

HANDOFF is an important aspect of cellular and mobile communication. Typically, an MT has a radio link to a BSS that provides “best service” to the mobile terminals currently located within a cell. A cell’s BSS provides a radio link to each mobile terminal active in this cell. One or more BSSs are in turn, under the control of an MSC. Besides other functions, an MSC has the primary responsibility of managing mobility. If and when an MT moves, it is quite possible that the currently serving BSS may no longer be able to provide reasonable quality of service as compared to some other BSS. Rather than dropping the service to this MT, the currently serving MSC may decide to hand over this service to some other better serving BSS or in some cases to another MSC. Several different handoff techniques have been proposed and implemented. A detailed survey of different handoff techniques deployed in various cellular networks can be found in [1], [2]. The simplest handoff scheme is the one in which the mobile terminal is solely responsible for making handoff decisions. When the received signal quality drops below an acceptable threshold, the MT may decide to choose another base station i.e., the handoff decision is made by the MT, as in the WACS [3], the DECT wireless systems [4] and the Mobile IP Networks [5]. Alternatively, the network can be assigned the sole responsibility of making handoff decisions, as in the integrated cellular wireless networks [6] and the first generation analog cellular networks. It makes logical sense to combine these two approaches so that handoff decisions can be made jointly by the network and the mobile terminals. This approach, called the mobile assisted hand off (MAHO), is currently being used in the second and third generation digital cellular networks, e.g., GSM [7], IS-54 and IS-136 DAMPS [8], [9]. In the MAHO scheme, while network makes the final handoff decisions, it is assisted by the mobile terminal in the handoff process. This assistance takes the form of serving BSS asking the MTs to periodically report their received signal quality (in terms of the RSSI and the BER values) from the surrounding base stations. In contrast to the hard handoff used in the previously cited handoff schemes, the CDMA digital cellular networks based on the IS-95 standard [10], WCDMA [11] and UMTS all use soft handoff. Soft handoff implies that an MT is able to ‘talk’ to more than one BSS simultaneously. This is technologically possible for the CDMA based multiple access, since an MT can tune to more than one chip code simultaneously. However, soft handoff is not technically convenient for the TDMA based GSM or DAMPS. Possibility of handing off calls from one cellular technology, e.g., DAMPS IS-54 to another, e.g., IS-95 CDMA has also been considered by the TIA/EIA standards committee and has been documented in their IS-41 standard [12]. The newer mobile IP based standards like the IEEE 802.16e [13] allows both, MT and the network to initiate and make handoff decisions. However, the criterion used for making handoff decisions is still based on the link quality alone.

It has been suggested in [14] that for a handoff to be processed successfully, the newly selected base station must have a free channel available for handling the handed off

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call. Otherwise the handed off call will run the risk of being dropped. Dropping an ongoing connection is highly undesirable. For voice calls, it not only causes annoyance to the users, dropped calls also imply increased wireless bandwidth consumption, since a dropped call has to be re-established, leading to unavoidable consumption of time and bandwidth. Implications of dropping a data call may have even more serious consequences. As an example, assume that a user has an MT attached to a laptop computer for setting up an FTP connection with a server. If such a data call is dropped mid way while carrying out a large file transfer, all the previously transferred file data may get lost, resulting in loss of time and bandwidth. With 2.5G and 3G wireless services laying greater emphasis on data services like GPRS [15], it has become even more pertinent to minimize any loss in performance due to dropped handoff calls. Lin et al. [14] suggested techniques for minimizing the call dropping probability due to non-availability of a channel. One such technique is to reserve one or more channels (called the guard channels) for handoff calls. Guard channels based reservation scheme has been analyzed in [1], [16], [17], [18] in terms of dropping probabilities (for handoff calls) and blocking probabilities (for new calls) using continuous time Markov chain (CTMC) models. The GSM technology, on the other hand, uses MAHO handoff in which the MSC makes handoff decisions solely on a single criterion of RSSI measurements reported by an MT. However, both the guard channel approach as well as the MAHO scheme can individually result in unnecessary loss of handoff calls. For example, in the MAHO scheme, it is possible that the serving BSS may end up handing off a call to another base station that has good signal quality, but there are no free channels available in the new base station to accept this handoff call. Similarly, when using the guard channel approach, since the signal strength is not taken into consideration while making handoff decisions, there is a finite probability that the serving base station may hand over call to a new base station that has poor signal quality. More recently, Kim et al. [19] suggest using multiple criteria, e.g., such as pilot signal strength (PSS), the distance between the mobile and the base station, the moving direction, and the previous location may be used to make fuzzy handoff decisions. To address limitations of single criterion handoff schemes, such as MAHO and guard channel, in this paper, we combine the MAHO and the guard channel based approaches and propose a new multi-criteria handoff technique referred to as "M+G" scheme. The proposed technique is analyzed along the lines in [16] by using a CTMC model. The resulting analysis shows that the proposed technique has better performance since it results in smaller call dropping probability.

The remainder of the paper is organized as follows: Section II highlights the need to combine signal quality information with the free channel availability information for processing the handoff calls. This is followed by the description of the CTMC model for the proposed handoff scheme obtained by combining MAHO and the guard channel approaches. Section III describes two different protocols that may be used to implement the proposed handoff scheme "M+G". Numerical and comparative results for the call dropping and call blocking probabilities under various operating conditions are presented in Section IV. Finally, Section V provides some concluding remarks.

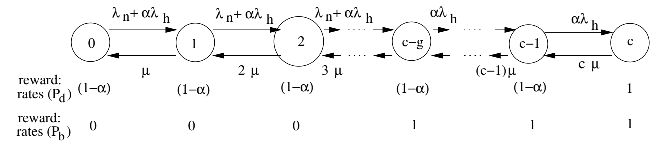

Fig. 1. Markov reward model

II. Effect of signal quality on handoff

To motivate the discussion for the new handoff scheme, it will be instructive to first analyze the effects of poor signal quality on the guard channel based handoff scheme discussed in [14], [20] and analyzed in [16]. The analysis in [16] presumes that a handed off call always has an acceptable signal quality. In real practice, however, there may be a small probability that such calls do not have adequate signal quality. In such situations, a channel will be allocated to a handoff call, but such a call can not be sustained by the new BSS due to poor signal quality. Let α ($\widetilde{\alpha} = 1 - \alpha$) be the probability that the system is processing a good (bad) signal quality handoff call. The assertion that $\alpha = 1$ is not true because all BSS are not going to provide same signal quality. Those closer to the MT may be having higher received signal strength indicator (RSSI) versus those BSSs that are further away from this MT. In fact, the standard MAHO makes decision only on the basis of RSSI. It means that for a given BSS, some of the handoffs for which it may be a good candidate (on the basis of channel availability), it may not have higher RSSI. A poor quality handoff call may either be dropped immediately or, it may be re-handed off to yet another BSS. The first technique is labeled as the "G+Drop" scheme, while the second one is referred to as the "G+ReHO" scheme. Subsequently, we also introduce the third scheme, called the "M+G", which is proposed in this paper and is based on the handoff technique obtained by combining the MAHO and the guard channel techniques. The proposed technique and a possible protocol for its implementation is described in the next section.

For the "G+Drop" scheme, the dropping and blocking probabilities may be computed by using the Markov reward model shown in Fig. 1. In this model, state i $(= 0, 1, \ldots, c)$ denotes the number of ongoing calls in a cell. The inter-arrival time between successive new calls is assumed to be a random variable with distribution $EXP(\lambda_n)$, where λ_n denotes the arrival rate for new calls. The inter-arrival time for the handoff calls is also assumed to be exponentially distributed with the parameter λ_h. Since any poor signal quality handoff call is immediately dropped, the effective incoming call traffic rate is $(\lambda_n + \alpha\lambda_h)$. Calls under progress in a cell are either completed or handed off to another cell. The call completion time is assumed to be exponentially distributed with the parameter μ_1. The time interval for which a received call stays in a cell before being handed off is also exponentially distributed with rate parameter μ_2. Therefore, the effective call service rate is given by $(\mu_1 + \mu_2)$. For computing dropping and blocking

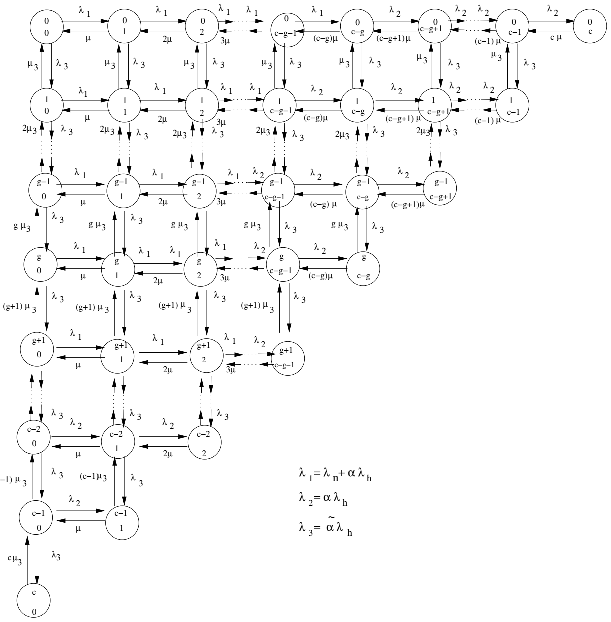

Fig. 2. Markov chain model

probabilities, we utilize a reward model which assigns a reward rate to each state. Given that there are a total of c channels available in a cell, for computing the dropping probability, states $(0, 1, \ldots, c-1)$ are assigned a reward rate of $(1-\alpha)$. This follows from the fact that in each of these states, there is a $(1-\alpha)$ probability of receiving a poor quality channel for a handoff call which is immediately dropped. The right most state c is assigned a reward rate of 1, since all handoff traffic is dropped in this state. The dropping probability is now given by the steady state expected reward rate which can be written as

$$P_d = \pi_c + (1-\alpha)\sum_{j=0}^{c-1} \pi_j \tag{1}$$

where, $\pi_j,\ j = 0, 1, \ldots, c$ is the steady state probability of finding the system in state j. These state probabilities are obtained by solving the balance equations for Fig. 1, which is essentially a birth-death process. Such processes have been extensively studied in the literature and we can use the solution derived in [21]

$$\pi_j = \pi_0 \begin{cases} \frac{\rho^j}{j!}, & j \le c-g \\ \frac{\rho^{c-g}}{j!}\rho_h^{j-(c-g)}, & j \ge c-g \end{cases} \tag{2}$$

where, $\mu = \mu_1 + \mu_2$, $\rho = \frac{\lambda_n + \alpha\lambda_h}{\mu}$ and $\rho_h = \frac{\alpha\lambda_h}{\mu}$ and,

$$\pi_0 = \frac{1}{\sum_{j=0}^{c-g-1} \frac{\rho^j}{j!} + \sum_{j=c-g}^{c} \frac{\rho^{c-g}}{j!}\rho_h^{j-(c-g)}}$$

For computing the blocking probability, states $(c-g, \ldots, c)$ will block any new incoming call since g channels are reserved for handoff only. Consequently, these states are assigned a reward rate of 1. Using (2), new call blocking probability P_b is given by

$$P_b = \sum_{j=c-g}^{c} \pi_j \tag{3}$$

It will be shown in the sequel, that for the "G+Drop" case, the dropping probability increases monotonically as $\tilde{\alpha}$ increases. In contrast, the performance with respect to the blocking probability marginally improves as $\tilde{\alpha}$ increases. This counter intuitive behavior can be explained by the fact that, as the poor signal quality handoff traffic increases, such calls are immediately dropped. Dropping such calls free up channels that may be used for the new incoming calls, thereby reducing new call blocking probability. Numerical results in Section IV will substantiate these observations.

The second scheme is labeled "G+ReHo", which reflects the fact it uses guard channels in conjunction with the re-handing of poor quality handoff calls to some other better serving BSS. To carry out the performance analysis of this scheme, we first need to derive a CTMC model that incorporates poor signal quality handoff calls as well. Fig. 2 shows the modified CTMC model which takes into account the fact that a handoff call has poor signal quality with non-zero probability $\tilde{\alpha} = (1-\alpha)$. Note that Fig. 2 captures the situation wherein, a poor signal quality handoff is not immediately dropped as in the "G+Drop" case. Instead, such a call can be re-handed off to some other BSS. The third scheme, called the "M+G" scheme, is a further improvement over the "G+ReHo" scheme. The "M+G" scheme utilizes MAHO in addition to the guard channels. In this scheme, even if a channel is available at a candidate BSS, a poor signal quality call is not handed over to it. Similarly, a good signal quality call is also not handed over to a BSS with no available channels. Thus, "M+G" scheme ensures that a handoff call is handed over to a BSS that is able to offer both good signal quality as well as an idle channel, thereby resulting in $\alpha \to 1$. From the point of view of modeling the "M+G" scheme, it turns out to be a limiting case of the previous two models shown in Fig. 1 and Fig. 2, with $\alpha \to 1$.

Each state of the CTMC in Fig. 2 is labeled as a tuple (i, j), where i denotes the number of 'poor' handoff calls being handled and j denotes the number of 'good' ongoing calls in this state. It is further assumed that there are $g\ (< c)$ guard channels set aside for the handoff calls. As in the previous model, the CTMC model shown in Fig. 2 assumes that the inter-arrival time distribution is $EXP(\lambda_n)$ for the new calls and $EXP(\lambda_h)$ for the handoff calls. Calls entering a cell either leave the system when completed or handed off to a different cell. The call completion time as well as the handoff time are both assumed to be random having $EXP(\mu_1)$ and $EXP(\mu_2)$ distribution, respectively. This implies that the total time spent by a call in a cell is also random having $EXP(\mu)$ distribution, and $\mu = \mu_1 + \mu_2$. In this model, since $\tilde{\alpha}$ fraction of handoff calls received by a particular cell are assumed to have poor signal quality, the receiving cell of such calls in turn needs to quickly re-handoff these calls to some other cell. The time spent by a poor quality handoff call in a cell is also assumed to be exponentially distributed with rate parameter μ_3. Generally, $\mu_3 >> \mu_2$, to reflect the fact that a good quality call is likely

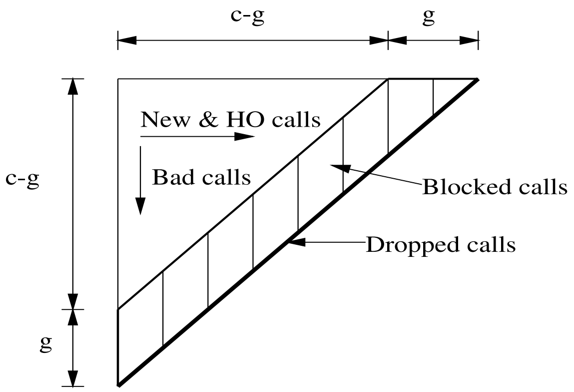

Fig. 3. Dropping and blocking states

to stay in a cell longer as compared to a poor signal quality call, which should be made to leave the cell quickly.

We obtain a closed form solution for the state probabilities of the CTMC in Fig. 2. For $0 < i, j \leq c, 0 < i + j \leq c$, the state probabilities are given by

$$\pi_{i,j} = \pi_{0,0}\left(\frac{\lambda_3}{\mu_3}\right)^i \prod_{k=0}^{j-1} \frac{\lambda_{i,k}}{(k+1)\mu}, \tag{4}$$

where

$$\lambda_{i,k} = \begin{cases} \lambda_1, & 0 \leq i+k < c-g \\ \lambda_2, & c-g \leq i+k < c \end{cases}$$

The derivation of the state probabilities is given in Appendix. The value of $\pi_{0,0}$ can be computed using the normalization equation

$$\sum_{i=0}^{c}\sum_{j=0}^{c-i}\pi_{i,j} = 1$$

After computing the steady state probabilities for various states (i, j), we can compute the performance in terms of the new call blocking probability P_b and the handoff call dropping probability P_d. To compute these probabilities, we first need to identify states in which a call may be blocked, dropped, or both. Fig. 3 graphically shows such states. Set of states identified by the thick line are the states $\{(i, c-i), 0 \leq i \leq c\}$, in which the system can support neither a handoff nor a new call, since no free channels are available in these states. The set of states forming the shaded region define the states in which only the handoff calls can be supported. Since only the guard channels are available in the states forming the shaded region, any incoming new call will be blocked in these states. Consequently, P_d and P_b can be written as

$$P_d = \sum_{i=0}^{c}\pi_{i,c-i} \tag{5}$$

$$P_b = \sum_{i=0}^{c-g}\sum_{j=c-g-i}^{c-i}\pi_{i,j} + \sum_{i=c-g+1}^{c}\sum_{j=0}^{c-i}\pi_{i,j} \tag{6}$$

where, $\pi_{i,j}$ is the steady state probability of the CTMC being in state (i, j) as given in (4). $\pi_{i,j}$'s were obtained via the closed form solution as well as numerically. The two sets of results were nearly identical. SHARPE software package was used to solve the CTMC shown in Fig. 2 to obtain $\pi_{i,j}$'s along with P_d and P_b. These results are discussed subsequently in Section IV.

The goal of a good handoff scheme is to make the dropping and blocking probabilities as small as possible. The proposed handoff scheme "$M + G$" achieves this goal by ensuring that any handoff call is sent to a cell that can provide a free channel as well as good signal quality which ensures $\alpha \rightarrow 1$. In the next section, we describe two possible handoff protocols for the proposed handoff scheme that may be used to achieve this goal.

III. GUARD CHANNELS AND MOBILE ASSISTED HANDOFF PROTOCOL

In the previous section, we analyzed a multi-criteria handoff technique in which an MSC makes handoff decisions based on two parameters, $viz.$, RSSI and channel availability. This section, describes two possible ways to implement this multi-criteria handoff scheme. This handoff scheme assumes that the controlling MSC assisted by the MT, makes and implements the handoff decisions. The controlling MSC makes these decisions based on (i) the downlink (BSS to MT) RSSI measurements are made by the MTs by measuring the signal strength of the forward control channel (FCCH) from different BSSs, (ii) Uplink (MT to BSS) channel information provided by the BSSs to the MSC periodically or when ordered to do so by the MSC, and (iii) channel availability at different base stations. The downlink RSSI measurements are made by an MT either periodically or on specific orders sent by its serving MSC. The channel availability in a cell can be evaluated in two different ways.

1) A BSS regularly broadcasts data about the number of free channels available with it. A BSS may send this information over its FCCH, (i.e., from the BSS to the MTs). FCCH, being a broadcast channel, information pertaining to the number of free channels currently available in a particular cell thus gets communicated to all the reachable MTs from a BSS. An MT also receives instructions from its serving MSC about the identity of the BSSs that are of interest to this MSC for eventually performing a handoff. In response to these instructions, an MT prepares its MAHO report consisting of RSSI information and the channel availability information associated with the indicated BSSs. Alternately, a BSS can use the in band signaling using the slow associated control channel (SACCH) to communicate channel availability information to a specific MT. Whether to use the FCCH or the SACCH is a matter of protocol details and is beyond the scope of this paper. Finally, when instructed to do so, the MT sends its MAHO report to the MSC. This report consists of the downlink RSSI information plus the channel availability information pertaining to BSSs that are potential candidates to take over the handoff. Note that since we have only modified the structure and contents of the MAHO report and not the MAHO protocol, this scheme will work for intra-BSS, inter-BSS or inter-MSC handoffs.

2) Each BSS keeps its MSC informed of its channel status, i.e., how many channels are being used by the number of new calls, handoff calls and the number of free guard channels over some infrastructure network. Typically, there is an infrastructure network that interconnect BSSs and MSCs and is used by BSS to report its channel availability information. In the context of a handoff, the uplink RSSI and channel availability information is provided by the BSSs to MSCs using such an infrastructure network. MSCs themselves are networked together over this infrastructure network and may communicate with each other using SS7 or some other similar protocol. When a handoff involves more than one MSC, the MSCs exchange channel availability data sets in addition to the RSSI sets.

In both these cases, a BSS informs its MSC about the need to handoff an MT to some other BSS. In the first case, the serving BSS forwards the RSSI and channel availability data compiled by the MT to the MSC. Based on this information, the MSC selects an appropriate BSS that should take over the handoff call. In the second scheme, the MSC asks the MT to forward its RSSI report via its serving BSS. Based on this report, the MSC identifies the candidate BSSs that can deal with this handoff. It then looks up its database to find the availability of channels at these candidate BSSs to arrive at the final decision. Irrespective of the architecture used for conveying free channel count information, the proposed handoff scheme will ensure that the new BSS receiving a handoff call will be able to provide a free channel as well good link quality, thus ensuring $\alpha = 1$, or very close to one.

IV. NUMERICAL RESULTS

To show the improvement provided by the new handoff scheme, we compare the relative performance of the four different handoff schemes:

1) "G+Drop" refers to the simple guard channel approach described in [16], [14], [20]. Any poor signal quality handoff call received by a BSS can not be sustained by this BSS and is simply dropped. The resulting model is shown in Fig. 1.
2) Simple "MAHO" [9] and [7] with no guard channels. This scheme is modeled by Fig. 1 with $\alpha = 1$ and $g = 0$.
3) "G+ReHo" scheme in which poor quality handoff calls are re-handed off as shown in the model in Fig. 2.
4) "M+G" scheme that utilizes the handoff protocol proposed in the last section, which because of MAHO leads to $\alpha \rightarrow 1$. This is modeled by Fig. 1 with $\alpha = 1$.

Performance of these handoff schemes is evaluated in terms of dropping and blocking probabilities P_d and P_b, respectively. Computation of these probabilities assume total number of channels $c = 12$ and the number of guard channels $g = 1, 2$. To evaluate the effect of poor signal quality handoff calls, we set $\alpha = 0.90$ for the purpose of numerical illustrations. It can be any other number (say 0.95 or 0.8), but with the restriction that $\alpha < 1$. Note that the analysis carried in [16] tacitly assumed $\alpha = 1$, whereas, its actual value may usually be less than 1. The model to be used when $\alpha < 1$ is given either by Fig. 1 or by Fig. 2, depending on whether the 'poor' quality handoff calls are dropped or are re-handed off, respectively. In the numerical computations, call completion rate μ_1 is taken to be 0.5 calls/min and μ_2, denoting the rate at which ongoing calls are handed off to some other BSS is assumed to be 0.5 calls/min. This gives $\mu = 1.0$. When a BSS receives a poor signal quality handoff call, such a call needs to be either dropped immediately or re-handed off quickly to some other BSS. For the latter case, μ_3 denotes the rate at which poor signal quality calls are re-handed off and is assumed to be 2.0 calls/min. The arrival rate of new calls λ_n is varied from 10 to 80 calls/min. Since $\mu = 1.0$, λ_n also represents the new call traffic load in Erlangs. The only other remaining parameter is the handoff arrival rate λ_h which needs to be computed from the respective fixed point equations as suggested in [16]. Consider now the different ways to handle a handoff as discussed at the beginning of this section:

"G+Drop" - In this case, since a handoff call with poor signal quality is immediately dropped by the receiving BSS, we can compute P_d and P_b using the Markov reward model shown in Fig. 1. The handoff rate for this model is computed on the basis of the following fixed point equation:

$$\lambda_h = \mu_2 \sum_{j=0}^{c} j \pi_j(\lambda_n, \mu_1, \mu_2, \alpha, \lambda_h) \tag{7}$$

Above equation is solved iteratively for λ_h using the SHARPE software package [22] and placing the fixed point code within the SHARPE code for this model. The proof of existence and uniqueness of the fixed point solution for (7) is similar to the proof given in [16].

MAHO - This scheme makes handoff decisions solely on the basis of signal quality (thus ensuring $\alpha = 1$) and does not take into account the availability of free channels or guard channels for the handoff calls. From the modeling and performance evaluation purposes, we can utilize the reward model as shown in Fig. 1 with $\alpha = 1$, $g = 0$ and the different reward rate assignments. For the MAHO case, states $(0, 1, \ldots, c-1)$ are assigned a reward rate of 0 and state c is assigned a reward rate of 1. The dropping as well the blocking probabilities are evaluated with fixed point equation (7) for computing λ_h.

"G+ReHo" - In this case, the receiving BSS of a poor signal quality handoff call, rather than dropping such a call (as was done in the previous case), re-hands it off to some other better serving BSS. For studying the behavior of this handoff scheme, we utilize the CTMC model shown in Fig. 2. λ_h again needs to be calculated using fixed point iterations. Consequently, we need to first set up the fixed point iteration equation associated with the CTMC model shown in Fig. 2. The basic logic behind the fixed point iteration is that, across a multi-cell cellular network, for given traffic and signal conditions, the net incoming handoff rate should equal the net outgoing handoff rate. For an arbitrary cell, we can use the CTMC shown in Fig. 2 to calculate these handoff rates. Any particular state (i, j) of this CTMC corresponds to the following traffic and

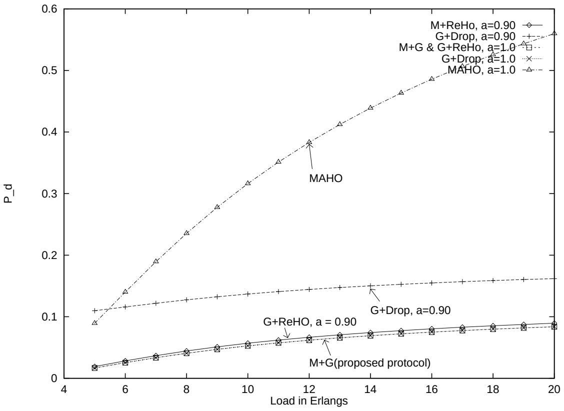

Fig. 4. Dropping probability (c=12, g=2)

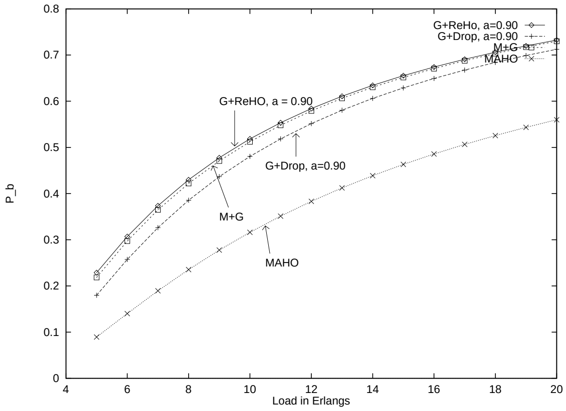

Fig. 5. Blocking probability (c=12, g=2)

signal conditions:

i : number of 'poor' signal quality handoff calls

j : number of 'good' signal quality ongoing calls

This would imply that any one of the i calls will get handed off at the rate μ_3 and any one of the j calls will get handed off at the rate μ_2. As a consequence of the fixed point argument for the handoff traffic, the net outgoing handoff traffic rate from this cell must equal the incoming handoff rate, $i.e.$,

$$\begin{aligned}\lambda_h &= \sum_i \sum_j i\mu_3 \pi_{i,j}(\lambda_n, \mu_1, \mu_2, \mu_3, \alpha, \lambda_h) \\ &+ \sum_i \sum_j j\mu_2 \pi_{i,j}(\lambda_n, \mu_1, \mu_2, \mu_3, \alpha, \lambda_h) \qquad (8)\end{aligned}$$

Obtaining a closed form solution for above fixed equation for λ_h is not feasible. Instead, we solve for λ_h iteratively by means of successive substitution. As was done previously, (8) can be solved within the SHARPE code itself. It was observed that the fixed point iterations usually converged within 4-6 iterations. It has been shown in [23] that the solution for fixed point iteration equation of the form (8) exists. However, the uniqueness of the fixed point solution remains to be shown. The resulting λ_h along with other parameters were then used to obtain P_d and P_b values.

"M+G"- The "M+G" case refers to the handoff scheme based on the proposed handoff protocol described in the previous section. The underlying handoff protocol ensures that when a call is to be handed off, it is handed off to a cell which is able to provide a free channel as well as acceptable signal quality, thus ensuring $\alpha \to 1$. For studying its performance behavior, the previous CTMC model (Fig. 1) may be used with $\alpha = 1$ and the corresponding fixed point equation (7).

Fig. 4 shows the behavior of P_d as a function of new traffic load in Erlangs for the four different handoff schemes. This plot assumes $c = 12$ and $g = 2$. To analyze the effect of poor signal quality handoff calls, α was set to 0.90. When α is reduced to 0.90, the performance of the "G+Drop" scheme deteriorates significantly. For the MAHO case, even though α is always 1, its dropping probability performance is inferior to the other three schemes because MAHO assumes $g = 0$, leading to greater number of handoff calls being dropped. The performance of the "G+ReHo" is slightly lower than that of the proposed "M+G" scheme, since poor signal quality handoff calls are not immediately dropped. Instead, such calls are re-handed off to some cell that can provide better service. Similar behavior was observed for $g = 1$ and $g = 3$. The only notable feature is that smaller number of guard channels result in slightly higher values of dropping probabilities for all the schemes except for the MAHO whose performance does not depend on g.

Fig. 5 shows the behavior of the new call blocking probability P_b for $c = 12$, $g = 2$ as a function of traffic intensity, for $\alpha = 1.0$ and 0.90. Similar to the behavior P_d, P_b is also seen to be a monotonically increasing function of the traffic intensity. Behavior of P_b as a function of α however, needs a closer examination. For the ideal case of $\alpha = 1.0$, the proposed schemes ("M+G") and "G+ReHo", as well as the conventional "G+Drop" scheme have identical performance. As α is reduced, the P_b performance of the "G+ReHo" scheme drops, as compared to the "M+G" and "G+Drop" schemes. This is explained by the fact that the "G+ReHo" scheme needs to temporarily allocate channels to the poor quality handoff calls. This in turn leaves fewer channels available for the new incoming calls, thereby increasing P_b. It is interesting to note that "G+Drop" scheme exhibits a slight improvement in P_b, as was explained in Section II. It should however be emphasized that a marginal improvement in the call blocking probability at the expense of greater increase in the dropping probability is hardly a desirable feature. Similar behavior was observed for $g = 1$ and $g = 3$. However, as g was increased, except for the MAHO all other schemes resulted in larger number of new calls being blocked, due to the fact that fewer channels are available for handling new calls as g is increased. The blocking probability performance of the MAHO scheme is the best amongst all the schemes described in this paper. This is quite expected, because MAHO ensures $\alpha = 1$, and since $g = 0$, all the c channels remain available for accepting new calls, thus reducing the new call blocking probability. Note however that, reduced blocking probability comes about at the expense of significantly higher dropping probability which is highly undesirable as pointed out earlier.

The final component of our analysis deals with the behavior of P_d and P_b as a function of α. This analysis is similar to the analysis carried out earlier for P_d and P_b as a function of

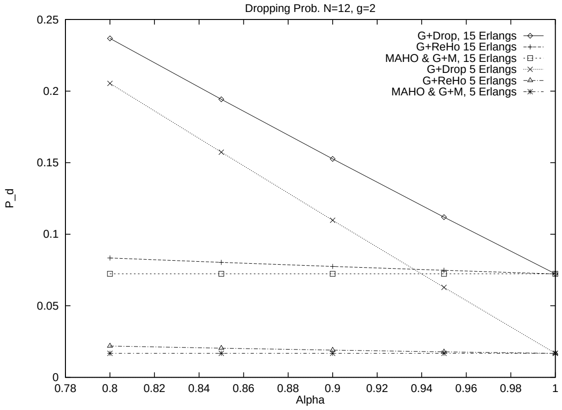

Fig. 6. Dropping probability vs. α (c=12, g=2)

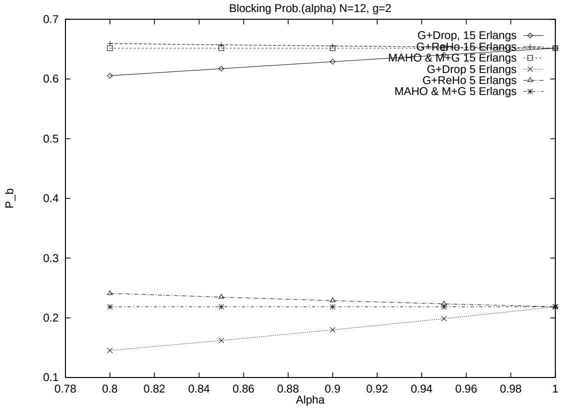

Fig. 7. Blocking probability vs. α (c=12, g=2)

traffic intensity. In the SHARPE code, we fixed the value of $g = 2$ and that of the traffic intensity to 5 and 15 Erlangs. The value of α was varied from 0.80 to 1.0. The effect of the changing α on P_d for the four different handoff schemes under consideration is shown in Fig. 6. As α is increased, the dropping probability for the "G+Drop" scheme reduces quite rapidly, as compared to the "G+ReHo" scheme. Note that the dropping probability is minimum and remains constant for the "M+G" and the MAHO ($g = 0$) schemes since both these schemes by virtue of using mobile assistance, ensure that $\alpha = 1$. Furthermore, as $\alpha \to 1$, the dropping blocking for all schemes converges to the same minimum value.

The effect of α on the new call blocking probability is depicted in Fig. 7. For the "M+G" and the MAHO schemes, P_b is invariant with respect to α. However, for the "G+Drop" scheme, as α increases, P_b also increases monotonically. This is due to the fact that increased value of α implies fewer handoff calls being dropped immediately, which leaves fewer channels available for accepting new calls, thus increasing P_b as α increases. In contrast, for the "G+ReHo", increased value of α implies fewer handoff calls being dropped or re-handed off. This leaves fewer free channels available for handling new incoming calls, thereby increasing P_b.

V. CONCLUSION

This paper has dealt with the issue of handoff in cellular communication systems, keeping in mind more realistic scenarios in which BSSs also have to deal with handoff calls having poor signal quality. The analysis carried out in this paper shows that ignoring the effects of poor signal quality handoff calls leads to deterioration in performance. To handle poor signal quality handoff calls, the paper describes two new handoff techniques. The "G+ReHo" scheme is based on the argument that it is better to re-handoff poor quality handoff calls to some other BSS, instead of simply dropping such calls. The "M+G" scheme combines MAHO and guard channel approaches, which leads to a handoff scheme that ensures $\alpha \to 1$. Two possible protocols for implementing the "M+G" scheme are also described. Proposed techniques are analyzed by first deriving a CTMC model with non-zero probability of poor signal quality handoff. Analysis of these CTMCs allows us to compute performance in terms of blocking and dropping probabilities as a function of traffic intensity as well as the signal quality of the handoff calls. It is shown that by taking into account both the signal quality as well as the availability of free channels for processing a handoff call, the proposed schemes are able to deliver better performance than the previously reported schemes.

APPENDIX

We prove the closed form solution, as given in (4) for the steady state probabilities of the CTMC in Fig. 2, by using the mathematical induction. For $0 \leq i, j \leq c,\ 0 < i + j \leq c$

$$\pi_{i,j} = \frac{\pi_{0,0}}{i!}\left(\frac{\lambda_3}{\mu_3}\right)^i \prod_{k=0}^{j-1} \frac{\lambda_{i,k}}{(k+1)\mu} \tag{9}$$

$$= \frac{\pi_{0,0}}{i!j!\mu^j}\left(\frac{\lambda_3}{\mu_3}\right)^i \prod_{k=0}^{j-1} \lambda_{i,k}, \tag{10}$$

and, for $0 \leq i, j \leq c + 1,\ 0 < i + j \leq c + 1$, the following holds

$$\pi_{i,j} = \frac{\pi_{0,0}}{i!j!\mu^j}\left(\frac{\lambda_3}{\mu_3}\right)^i \prod_{k=0}^{j-1} \lambda_{i,k} \tag{11}$$

Solution: We find the steady state probabilities for the state $(0, c + 1),\ (c + 1, 0)$ and $(i, j),\quad 0 < i, j < c + 1$. Consider three cases separately.
For the state $(0, c + 1)$, the balance equation is given as

$$(c + 1)\mu\pi_{0,c+1} = \lambda_{0,c}\pi_{0,c}$$

$$\pi_{0,c+1} = \frac{\lambda_{0,c}}{(c + 1)\mu}\pi_{0,c}$$

Substitute for $\pi_{0,c}$ from (10), we get

$$\pi_{0,c+1} = \frac{\lambda_{0,c}}{(c + 1)\mu}\frac{\pi_{0,0}}{0!c!\mu^c}\left(\frac{\lambda_3}{\mu_3}\right)^0 \prod_{k=0}^{c-1} \lambda_{0,k}$$

$$= \frac{\pi_{0,0}}{(c + 1)!\mu^{c+1}}\left(\frac{\lambda_3}{\mu_3}\right)^0 \prod_{k=0}^{c} \lambda_{0,k}$$

which proves (11) for the state $(0, c + 1)$.

For the state $(c+1,0)$, the balance equation is given as

$$\begin{aligned}(c+1)\mu_3\pi_{c+1,0} &= \lambda_3\pi_{c,0}\\ \pi_{c+1,0} &= \frac{\lambda_3}{(c+1)\mu_3}\pi_{c,0}\end{aligned}$$

Substitute for $\pi_{c,0}$, we get

$$\begin{aligned}\pi_{c+1,0} &= \frac{\lambda_3}{(c+1)\mu_3}\frac{\pi_{0,0}}{c!0!\mu^0}\left(\frac{\lambda_3}{\mu_3}\right)^c\\ &= \frac{\pi_{0,0}}{(c+1)!0!\mu^0}\left(\frac{\lambda_3}{\mu_3}\right)^{c+1}\end{aligned}$$

which is in accordance with equation (11) for this state.

The third case requires equation (11) hold true for $0 < i, j < c$ such that $i + j = c$, i.e., the states lying along the diagonal in Fig. 2. The balance equation for these states can be written as

$$\lambda_3\pi_{i-1,j} + \lambda_{i,j-1}\pi_{i,j-1} = i\mu_3\pi_{i,j} + j\mu\pi_{i,j}$$

Substituting for $\pi_{i,j}$ from (10) gives

$$\begin{aligned}&\frac{\lambda_3}{(i-1)!j!\mu^j}\pi_{0,0}\left(\frac{\lambda_3}{\mu_3}\right)^{i-1}\prod_{k=0}^{j-1}\lambda_{i,k}\\ &+\frac{\lambda_{i,j-1}}{i!(j-1)!\mu^{j-1}}\pi_{0,0}\left(\frac{\lambda_3}{\mu_3}\right)^{i}\prod_{k=0}^{j-2}\lambda_{i,k}\\ &= \frac{i\mu_3}{i!j!\mu^j}\pi_{0,0}\left(\frac{\lambda_3}{\mu_3}\right)^{i}\prod_{k=0}^{j-1}\lambda_{i,k} + \frac{j\mu}{i!j!\mu^j}\pi_{0,0}\left(\frac{\lambda_3}{\mu_3}\right)^{i}\prod_{k=0}^{j-1}\lambda_{i,k}\end{aligned}$$

In the above equation, the first (second) term on LHS simplifies to the first (second) term on the RHS, thus proving the desired assertion.

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