A Method for Multiple Channel Recovery in TDMA Wireless Communications Systems

Yue Ma[a], James J. Han[a] and Kishor S. Trivedi[b]

[a]*Global Software Group, Motorola, Inc., 50 NW Point Blvd., 2FL, Elk Grove Village, IL 60007-1032, USA*

[b]*Center for Advanced Computing and Communication (CACC), Department of Electrical and Computer Engineering, Duke University, Durham, NC 27708, USA*

Abstract

A single base repeater failure in TDMA wireless systems causes all active calls on this base repeater to be dropped. In order to increase system end-to-end availability, a multiple channel recovery method for TDMA wireless systems is proposed in this paper. By applying the method, when a base repeater fails, the channels of active calls carried by the base repeater are replaced by working channels in the channel pool of the base site. All the active calls continue without the intervention of end users. The method deals not only with the failure and recovery of base repeaters, but also with the channel failure recovery in handoff processes, transient channel failures, and new call setup processes. To predict system availability and performance, hierarchical stochastic reward net (SRN) models are developed for analyzing channel allocation, base repeater failure/repair, and channel recovery. The results show that the recovery method can nearly eliminate dropped calls when the traffic load is light, and can dramatically reduce dropped calls when the traffic load is normal. The price we pay is a slightly increased blocking probability, nearly transparent to the end users.

Key words: Channel Failure, Fixed-point iteration, Markov reward models, Restoration Techniques, Stochastic Reward Nets, TDMA.

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1 Introduction

In wireless communications systems, the base site controller (BSC) handles radio channel allocation and many other functions. To date, BSC only han-

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Email addresses: yue.ma@motorola.com (Yue Ma), cjh048@email.mot.com (James J. Han), kst@ee.duke.edu (Kishor S. Trivedi).

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dles channel allocation for new calls and handoff calls, no channel failures of ongoing calls are recovered. Whenever a channel fails, the call carried by the channel will be dropped. There are many factors that cause channel failures, for example, power failure, radio frequency (RF) amplifier failure, shadowing, etc. Some of the failures can be categorized as permanent, while the others as transient. To reduce dropping probability, a channel recovery method is proposed in this paper. Both permanent and transient failure recoveries for time division multiple access (TDMA) wireless systems are considered.

The permanent channel failures are caused by equipment failures of base repeaters, such as power failure or RF amplifier failure, etc. In this paper, we assume that a base repeater (BR) can be found in failure status under two situations:

(1) While there are some ongoing calls on the BR, the BR is down.
(2) A BR may go down while it is in idle status (no ongoing calls on the BR). Thus when a call attempting to access a channel on that BR will acquire a faulty channel.

The transient channel failures are caused by many factors in the RF transmission, such as fading, shadowing and interference.

In our recovery method, a failed channel is automatically switched to an idle channel, if one is available. Otherwise, the call with a failed channel is queued until an idle channel is available. Our method is quite similar to the Automatic Protection Switching (APS) [17] scheme, which is widely used to enhance the network integrity in ATM networks. In APS systems, a failed network component is switched to an identical spare component when the protection switch detects a failure. Since the spectrum resource is limited, no spare channels are reserved exclusively for the calls with failed channels. However, failed calls are treated with the same priority as the handoff calls in the sense that both of them can access any available channel in the reserved channel pool.

For numerical evaluation of the recovery method, a hierarchical stochastic reward net (SRN) [2,3] model is developed. For comparison purposes, an SRN model is also developed for describing the behavior of a base site without recovery mechanism. The numerical results show that the recovery method can nearly eliminate dropped calls under light traffic; it can also dramatically reduce dropped calls under normal traffic. Even under heavy traffic, the method still improves the system performance by decreasing the dropping probability considerably. At the same time, the blocking probabilities are increased slightly. This is because some of the idle channels are used to recover the failed calls. In the non-recovery method, these idle channels would be otherwise used for accepting new calls.

This paper is organized as follows. In Section 2, we give an introduction to some of the features of the TDMA systems which are related to the recovery scheme. In Section 3, a brief introduction to SRN is given. In Section 4, we describe the channel recovery scheme. Hierarchical SRN models for comparing the recovery and the non-recovery methods are presented in Section 5. In Section 6, numerical results are presented and discussed. Finally, we make our conclusions in Section 7.

2 System Description

TDMA systems divide each radio channel into N time slots. Each time slot can be assigned to a different mobile subscriber (MS). The TDMA system that we are investigating consists of a base site controller and many base repeaters. In this paper, an IS-136 [13] TDMA system is assumed. Six subscribers ($N = 6$) can share a single radio channel. In the remainder of this paper, when we speak of a channel, we mean a time slot on a single radio channel.

A TDMA base repeater failure can cause multiple permanent channel failures. In this paper, it causes 6 permanent channel failures, which can be either in use or idle. The BR failure recovery has to restore all the active calls carried by the failed BR. There are some scenarios in which single channel failure occurs, for example, a call can be blocked by a moving/permanent object. This kind of call failure is referred to as the transient failed call (TFC) in our paper. An active call carried by a failed BR is denoted as BFC. A failed call (FC) can be either a BFC or a TFC.

The dropping of a handoff call (HC) is considered more severe than the blocking of a new call (NC). One method [7,14,15] to reduce the dropping probability of HC is to reserve a number of channels exclusively for HC. For example, if the total number of channels is C and the number of the channels in the reserved channel pool is g, then the number of channels available for NC is $C - g$.

3 Introduction to SRN

Stochastic reward net (SRN) [3] is an extension of Petri net (PN) [1,2], which is a high level description language for formally specifying complex systems. A PN is a bipartite directed graph with two types of nodes: *places* and *transitions*. Each place may contain an arbitrary (natural) number of *tokens*. For a graphical presentation, places are depicted as circles, transitions are represented by bars and tokens are represented by dots or integers in the places. Each transition may have zero or more *input arcs*, coming from its input places;

and zero or more *output arcs*, going to its output places. A transition is *enabled* if all of its input places have at least as many tokens as required by the multiplicities of the corresponding input arcs. When enabled, a transition can *fire* and will remove from each input place and add to each output place the number of tokens corresponding to the multiplicities of the input/output arcs. A *marking* depicts the *state* of a PN which is characterized by the assignment of tokens in all the places.

Generalized stochastic Petri nets (GSPNs) [1] extend the PNs by assigning a *firing time* to each transition. Transitions with exponentially distributed firing times are called *timed* transitions while the transitions with zero firing times are called *immediate* transitions. A marking in a GSPN is called *vanishing* if at least one immediate transition is enabled; otherwise it is called a *tangible* marking. Under the condition that only a finite number of transitions can fire in finite time with non-zero probability, it can be shown that a given GSPN can be reduced to a homogeneous continuous time Markov chain (CTMC) [1].

In order to make more compact models of complex systems, several extensions are made to GSPN, leading to the SRN. One of the most important features of SRN is its ability to allow extensive marking dependency. In an SRN, each tangible marking can be assigned one or more *reward rate(s)*. Parameters such as the firing rate of the timed transitions, the multiplicities of input/output arcs and the reward rate in a marking can be specified as functions of the number of tokens in any place in the SRN. For an SRN, all the output measures are expressed in terms of the expected values of the reward rate functions. To get the performance and reliability/availability measures of a system, appropriate reward rates are assigned to its SRN. In this paper, we use the tool SPNP [4] to specify and solve the SRN models.

4 A Channel Recovery Method in TDMA Wireless Systems

The channel recovery method is mainly composed of three processes: monitoring process, channel allocation process and BR failure handling process. They are described in detail in the following subsections.

4.1 Monitoring Process

In order to detect and handle base repeater failures, a base repeater monitoring process is developed as shown in Figure 1. Similar monitoring steps are developed for handoff and transient failure processes, which are not shown here.

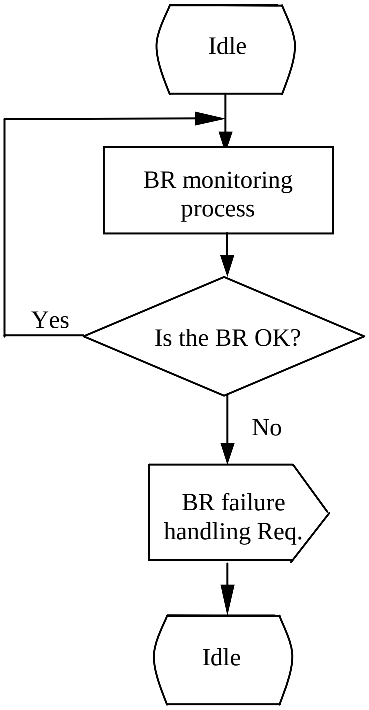

Fig. 1. BR monitoring process.

4.2 Channel Allocation Process

The RF channel allocation process consists of five parts: (1) algorithm to handle NC; (2) algorithm to handle HC; (3) algorithm to handle base repeater failure; (4) algorithm to handle transient failure; and (5) algorithm to update base repeater repair status. They are shown in Figure 2.

- NC Req.: When a new call set-up process starts, a NC channel request is initiated for a channel from the available channel pool.
  - If there are more than g channels available in the pool, then a channel is obtained. Furthermore, if the channel is in working condition, then the call is set-up, and the number of available channels is decreased by 1. Otherwise, if the channel is bad, three actions will be taken:
    1. a new channel request is issued;
    2. reduce the total number of idle channels by N;
    3. a base repeater repair request is issued.

    The new channel request may be put into the NC channel request queue if there are less than g+1 idle channels in the channel pool.
  - For an initial NC request, if there are less than g+1 idle channels, the call will be blocked.
- HC/BFC/TFC Req.: When a HC/BFC/TFC request is initiated, it requires an idle channel from the channel pool. The handling procedure is similar to that of the NC request. The only difference is that as long as there is a single

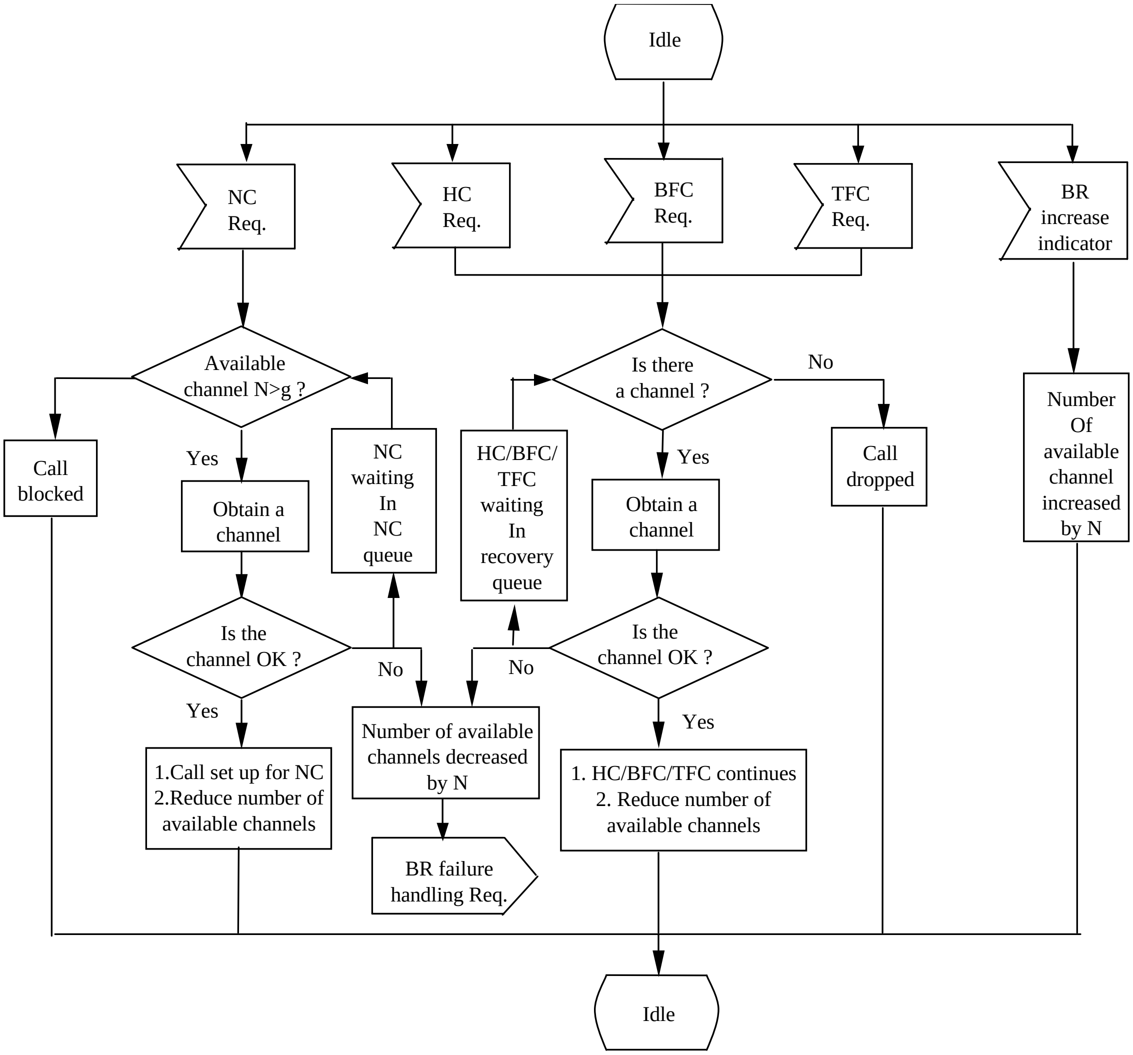

Fig. 2. Channel allocation process message sequence chart.

idle channel in the channel pool, it can be obtained by HC/BFC/TFC.

- BR Repair Update: Whenever a BR increase indicator message is received, the channel allocation process increases the total number of available channels in the channel pool by N.

4.3 Base Repeater Failure Handling Process

The base repeater failure handling process (Figure 3) is consisted of two parts:

(1) Procedure to update system parameters when a BR repair is completed;
(2) Procedure to handle a BR failure handling requirement.

After a BR is repaired, the total number of BR in service is increased by 1. A BR increase indicator message is sent to the channel allocation process.

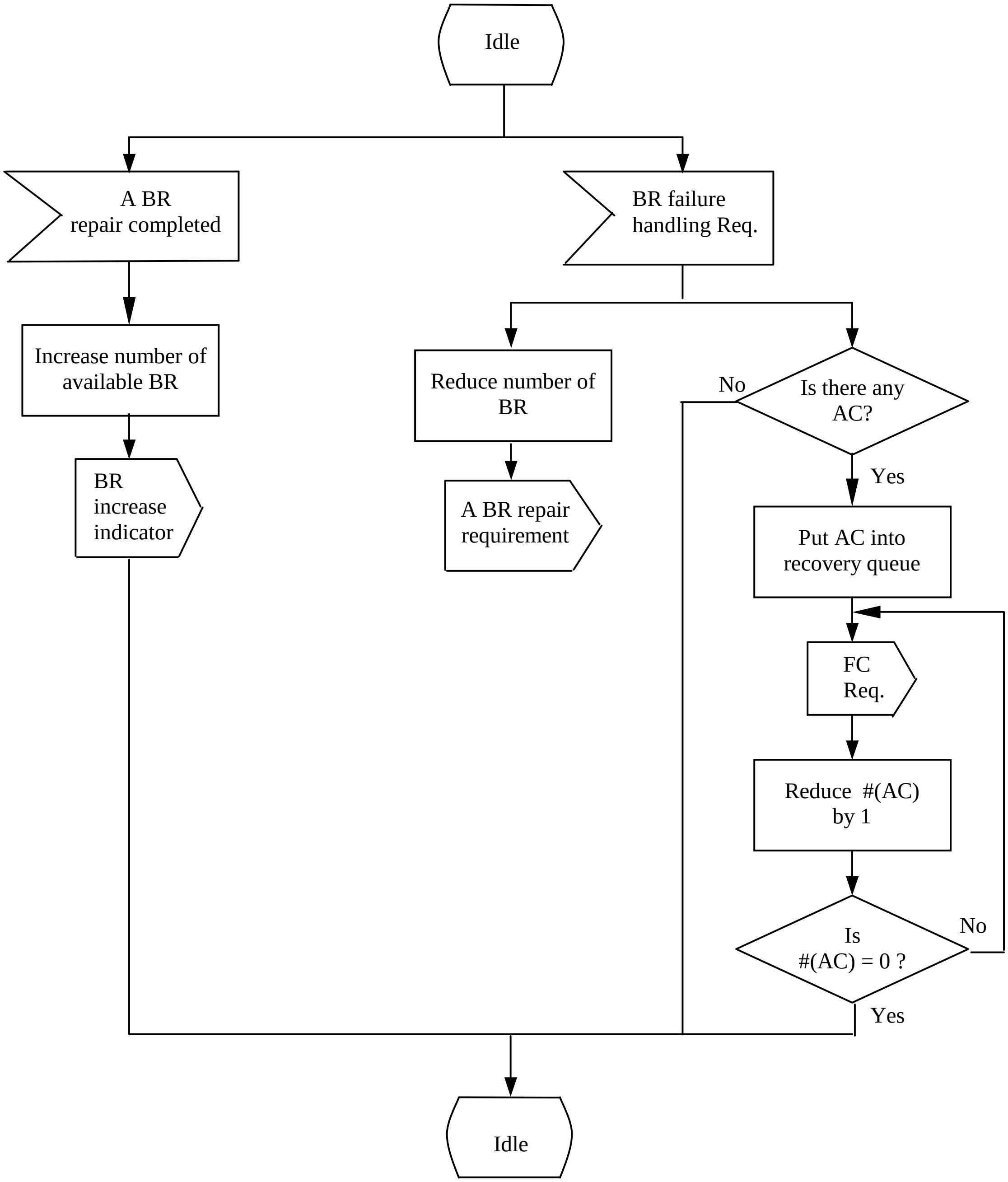

Fig. 3. Message sequence chart for BR failure handling process.

When a BR failure handling request is received from the BR monitoring process, the total number of available BR in service is decreased. In addition, the BR repair process is triggered. At the same time, the process also checks whether there is any AC on the failed BR. If the answer is no, no further action is required. Otherwise, the ACs are put in the recovery queue. A BFC request is sent to the channel allocation process for W times, where W is the number of ACs and $W \leq N$.

The BR repair process is relatively simple. When a BR repair request is received from the BR failure handling process, the BR repair process is triggered. After one BR is repaired, a BR repair completed message is sent back to the BR failure handling process. The repair process continues until all the failed BRs are repaired.

4.4 A Hierarchical SRN Model for the Channel Recovery Method

Based on the channel allocation and repair process described above, SRN models are constructed to analyze their performance. Because of the interactions among the base repeaters in a base site, an SRN model for a base site would instigate a huge state space for the underlying Markov reward process. Due to the nature of the system to be modeled, we employ a hierarchical approach to model the channel allocation, failure and recovery behavior in a base site. A two-level hierarchical SRN model is constructed:

(1) The higher level (Figure 4) models the overall behavior (channel allocation, channel failure and recovery) of a base site (BS).
(2) The lower level (Figure 5) models the detail of working, failure and recovery status of a generic base repeater (BR) in a base site.

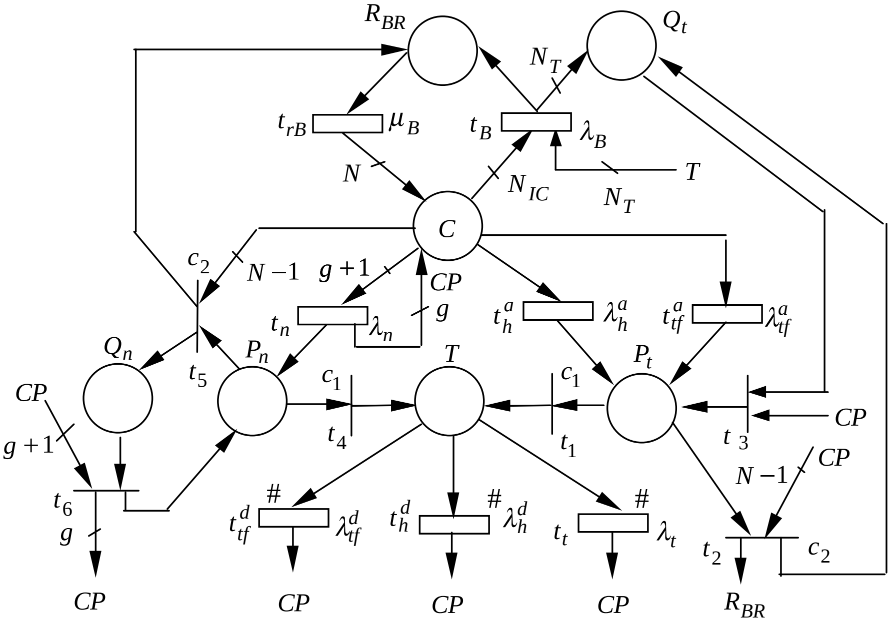

Fig. 4. Higher level for the recovery scheme: model for a base site.

In Figure 4, Place CP is the channel pool for the remote site. The number of channels assigned to the site is $C = N \cdot M$, where N is the number of channels a BR can support and M is the number of base repeaters that a base site has. Transitions t_n, t_h^a, t_B and t_{tf}^a represent the arrivals of NCs, HCs, BFCs and TFCs, respectively. Transition t_n is disabled if there are less than $g+1$ channels in Place CP, where g is the number of channels reserved for ongoing calls, which include HC and FC.

On the left side of Figure 4, at Place P_n, a NC has already obtained an idle channel, which is about to be tested for its working status. There are two possible outcomes of the test:

(1) With probability c_1 and the immediate Transition t_4, the channel obtained is in working condition, and the NC is set-up in Place T.

(2) With probability $c_2 = 1 - c_1$ and the immediate Transition t_5, the channel obtained is in non-working condition. From our assumptions in Section 1, this also implies that the BR carrying the channel is in bad condition. Through Transition t_5, $N-1$ channels from the same BR are removed from the channel pool, and the bad BR is deposited into the BR repair pool R_{BR}. The NC is deposited into the waiting queue Q_n. If there are more than g idle channels in the channel pool, the NC needs not wait. The immediate transition t_6 is fired instantly. Again the idle channel is tested in Place P_n. If there are less than $g+1$ channels in the channel pool, the NC needs to wait in the queue Q_n.

On the right side of Figure 4, at Place P_t, an HC/FC has already grabbed an idle channel. Transitions t_1 and t_2 have similar functions as their counterparts t_4 and t_5, respectively. If the idle channel obtained is in non-working condition, the HC/FC stays in Place Q_t before it fetches another idle channel through Transition t_3.

A channel is released under one of the following four situations:

(1) Normal termination of a call, represented by Transition t_t.
(2) Handoff departure to another cell, represented by Transition t_h^d.
(3) Transient failure, represented by Transition t_{tf}^d.
Transitions t_{tf}^d, t_h^d and t_t have marking dependent firing rates. Their firing rates are proportional to the number of tokens in Place T. This is represented by the sharp sign # beside the transitions.
(4) BR failure, represented by Transition t_B. When a BR fails while there are some active calls on this BR, the BFCs will be recovered by being put into the queue Q_t. The number (denoted by N_T) of active calls on a failed BR is obtained from the lower level model (Figure 5) for a generic BR. At the same time, N_{IC}, the number of idle channels, will be removed from the channel pool CP. $N_{IC} = N - N_T$ is the expected number of idle channels when a generic BR fails. The firing rate (λ_B) of Transition t_B should equal to $M_a \cdot \Lambda_B^g$, where M_a is the expected number of working BRs in a base site, i.e., $M_a = M - E[\#(R_{BR})]$, Λ_B^g is the throughput of Transition t_B^g for a generic BR. In the rest of this chapter, we use Λ to

denote the throughput of a transition.

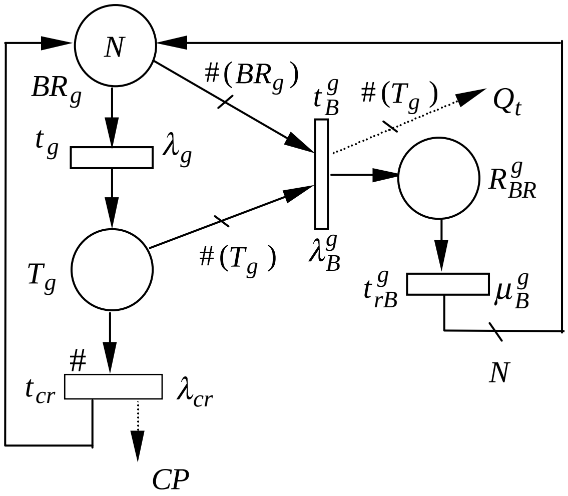

Fig. 5. Lower level for the recovery scheme: model for a base repeater (BR).

When a BR is recovered through Transition t_{rB}, N channels are added back into the channel pool. This is shown by the arc from Transition t_{rB} to Place CP.

Figure 5 models a generic BR in a base site. Transition t_g represents the actual job arrivals for each BR. Transition t_{cr} represents the release of a single channel. Its rate equals to $\lambda_t + \lambda_h^d + \lambda_{tf}^d$. We assume that the job handling is fairly distributed among the working BRs in a base site. Under this assumption, the firing rate λ_g is obtained through

$$\lambda_g = \frac{1}{M_a} \cdot (N_T \cdot \Lambda_B + \Lambda_h^a + \Lambda_n + \Lambda_{tf}^a). \tag{1}$$

The failure of a generic BR is represented by the Transition t_B^g. When a BR fails, all the tokens from Places BR_g and T_g will be flushed out. The dashed arc from Transition t_B^g to Place Q_t represents the relationship between the base site and a generic BR. It shows that the expected number of talking channels will be recovered through Place Q_t. Transition t_{rB}^g represents the expected repair time for a generic BR. We assume that at most three BR (an ultra-rare event) can be down at the same time in a base site, the average repair time for each BR is k hours. Then the expected weighted repair time for a generic BR is calculated through the following formula:

$$\frac{1}{\mu_B^g} = \frac{k \cdot P_R^1 + 1.5k \cdot P_R^2 + 2k \cdot P_R^3}{P_R^1 + P_R^2 + P_R^3}, \tag{2}$$

where μ_B^g is the expected repair rate for a generic BR, P_R^j is the probability that there are j BRs in Place R_{BR}, $j \in [1, 3]$.

Assuming a single repair facility, we obtain the weight 1.5 in (2) as following. When 2 BRs are down, it takes k hours to repair the first BR. When the 2nd BR is repaired, a total of $2k$ hours have passed by. From an observer's point of view, it takes an average of $(k + 2k)/2 = 1.5k$ hours to repair a single BR when 2 BRs are down. The weight 2 in (2) is obtained in a similar manner.

4.5 Fixed-Point Iteration

With different NC arrival rates, the parameters N_R, Λ_B^g, Λ_h^d, N_T and Λ_{tf}^d vary accordingly. To capture their dynamic behavior, a fixed-point iteration scheme [5,9] is applied to determine the above parameters. The values of these parameters are calculated as following,

$$N_R = \sum_{j \in \Omega_h} (\#[(R_{BR})_j])\pi_h^j(N_R, \Lambda_B^g, \Lambda_h^d, N_T, \Lambda_{tf}^d), \tag{3}$$

$$\Lambda_B^g = \sum_{j \in \Omega_l} \lambda_B^g \pi_l^j(N_R, \Lambda_B^g, \Lambda_h^d, N_T, \Lambda_{tf}^d), \tag{4}$$

$$\Lambda_h^d = \sum_{j \in \Omega_h} (\#[T_j])\lambda_h^d \pi_h^j(N_R, \Lambda_B^g, \Lambda_h^d, N_T, \Lambda_{tf}^d), \tag{5}$$

$$N_T = \sum_{j \in \Omega_l} (\#[(BR_g)_j])\pi_l^j(N_R, \Lambda_B^g, \Lambda_h^d, N_T, \Lambda_{tf}^d), \tag{6}$$

$$\Lambda_{tf}^d = \sum_{j \in \Omega_h} (\#[T_j])\lambda_{tf}^d \pi_h^j(N_R, \Lambda_B^g, \Lambda_h^d, N_T, \Lambda_{tf}^d), \tag{7}$$

where Ω_h and Ω_l are the sets of tangible markings of the higher (Figure 4) and the lower (Figure 5) level models, respectively. $\#[(R_{BR})_j]$, $\#[T_j]$ and $\#[(BR_g)_j]$ respectively denote the number of tokens in Place R_{BR}, T or BR_g in marking (state) j. $\boldsymbol{\pi_h}$ is the steady-state probability vector of the higher model and $\boldsymbol{\pi_l}$ is the steady-state probability vector of the lower model. Because of the interdependency between the higher and the lower models, $\boldsymbol{\pi_h}$ and $\boldsymbol{\pi_l}$ are functions of N_R, Λ_B^g, Λ_h^d, N_T and Λ_{tf}^d. In [9], Equations (3)-(7) are defined as the *fixed-point equations*. According to Theorem 2 in [9], a fixed point will exist if :

- The functions of $\boldsymbol{\pi_h}$ and $\boldsymbol{\pi_l}$ are weighted sums of state probabilities and the weights are constants;
- The CTMCs underlying the SRNs are irreducible with more than one state.

It is easy to verify that the two SRN models that we have developed satisfy the above two conditions. Therefore, fixed-points exist for (3)-(7).

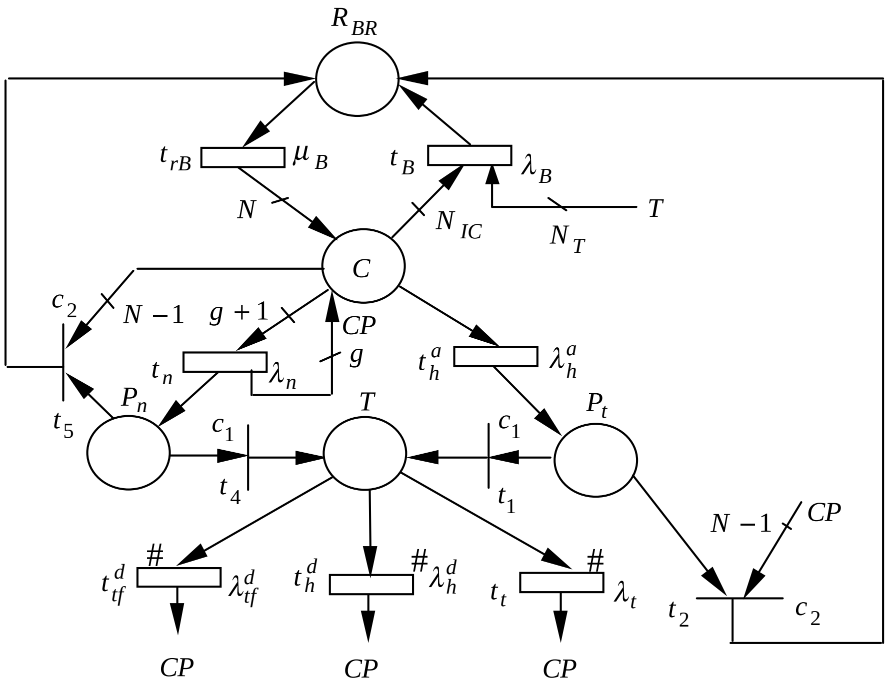

Fig. 6. Higher level (BS) model for the non-recovery scheme.

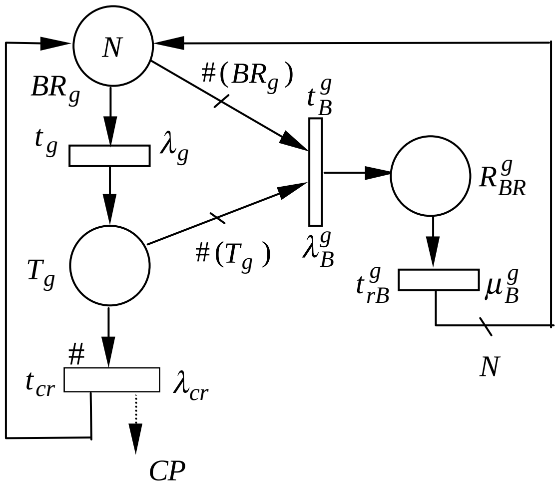

Fig. 7. Lower level (BR) model for the non-recovery scheme.

4.6 A Hierarchical SRN Model for the Channel Allocation without Recovery

For comparison purposes, a hierarchical SRN model for channel allocation without recovery is developed and shown in Figures 6 and 7. The notations of places and transitions are respectively the same as those in Figures 4 and 5.

In the non-recovery scheme, the following calls are dropped instead of recovered:

(1) Accepted HCs, but the BR assigned to them is in failure status.
(2) The active calls on a failed BR.
(3) TFC.

Consequently, the places Q_n and Q_t as in Figure 4 are removed in Figure 6.

When a NC is accepted, but the BR assigned to it is down, the accepted NC is blocked. As a result, the actual job arrival rate for a BR now becomes $\lambda_g = (1/M_a) \cdot (\Lambda_h^a + \Lambda_n)$. All the other input parameters for the non-recovery model are the same as those in the recovery model.

To obtain the numerical results, a fixed-point iteration scheme similar to the one presented in Section 4.5 is applied here.

4.7 Numerical Measures

Call Dropping Probability

We denote the dropping probabilities for the recovery method and non-recovery methods as P_{dr} and P_{dn}, respectively. To calculate P_{dr}, the reward rate assignment is:

$$r_{dr}^j = \begin{cases} 1 \text{ if } [\#(CP_j)] = 0, \\ 0 \text{ otherwise.} \end{cases} \tag{8}$$

Here r_{dr}^j is the reward rate for state j in the CTMC of SRN, and $\#(CP_j)$ represents the number of channels in Place CP in marking (state) j. Thus a reward rate of 1 is assigned to the states where the channel pool is empty [12,16], and a reward rate of 0 is assigned to the other states. Then P_{dr} is calculated by

$$P_{dr} = \sum_{j \in \Omega_h} r_{dr}^j \pi_h^j.$$

The dropping probability for the non-recovery method is calculated through the following expression:

$$P_{dn} = P_{ch}^e + P_d. \tag{9}$$

The first term of (9) is the probability that the channel pool is empty. The reward rates for P_{ch}^e are the same as in (8). The following formula is used to calculate P_d:

$$P_d = \frac{\Lambda_d}{\Lambda_{ta}}, \tag{10}$$

where Λ_d is the actual dropping rate for the accepted calls. It is contributed by the following three factors:

(1) A handoff call obtains a non-working BR, so it is dropped;
(2) The call is dropped while it is in talking status because the BR it holds fails;
(3) An ongoing call is dropped due to transient failure.

In summary, Λ_d is calculated through $\Lambda_d = c_2 \cdot \Lambda_h^a + N_T \cdot \Lambda_B + \Lambda_{tf}^d$. The denominator Λ_{ta} in (10) is the total accepted call rate for the base site. It is calculated through $\Lambda_{ta} = \Lambda_n + \Lambda_h^a$.

Call Blocking Probability

We denote the blocking probabilities for the recovery and non-recovery methods as P_{br} and P_{bn}, respectively. To calculate P_{br}, a reward rate of 1 should be assigned to the states where the channel pool has less than $g+1$ channels, that is

$$r_{br}^j = \begin{cases} 1 \text{ if } [\#(CP_j)] \leq g, \\ 0 \text{ otherwise.} \end{cases} \tag{11}$$

The blocking probability for the non-recovery method is calculated through the following expression:

$$P_{bn} = P_{ch}^g + P_b. \tag{12}$$

The first term of (12) is the probability that the channel has less than $g+1$ channels. It has the same reward rate as in (11). P_b is the probability that a new call is accepted, but the BR it obtains is in failure status. To calculate P_b, we use the following formula:

$$P_b = \frac{c_2 \cdot \Lambda_n}{\Lambda_{ta}}.$$

Call Waiting Time

In the recovery method, after obtaining a faulty channel, a new call may wait in place Q_n before accessing a working channel. Likelywise, an ongoing call may stay in place Q_t before being restored to the talking status again. The expected call waiting times for the new calls and the ongoing calls are denoted as W_n and W_o, respectively. For a new call or an ongoing call, we assume that the probability of obtaining two faulty channels consecutively is zero. In other words, for a call waiting in Q_n or Q_t, its probability of obtaining a working channel is one. In the following, Little's formula [2] is applied to obtain the values for W_n and W_o:

$$W_n = \frac{E[\#(Q_n)]}{c_2 \cdot \Lambda_n},$$

$$W_o = \frac{E[\#(Q_t)]}{c_2 \cdot (\lambda_h^a + \Lambda_{tf}^a) + \Lambda_B \cdot N_T}.$$

5 Numerical Results and Discussions

Under the assumption that all the neighboring cells are statistically identical and behave independently, the characteristics of the overall system can be captured by focusing on a single cell. In our system, all the cells are treated equivalently so that we can concentrate our attention on the performability [6,10] aspects of the channel recovery method. By varying the traffic parameters and developing additional submodels, the presented modeling technique can also be applied to the non-homogeneous cases where cells are located at the border of the covered area. An example of this is discussed in [8].

For the purpose of discussion, we assume that a set of $M = 8$ BRs are assigned to a base site. At the base site, $g = 1$ out of C channels is reserved exclusively for the HC/FC. The average handoff rate $(1/\lambda_h^d)$ is once per five minutes. The expected call holding time $(1/\lambda_t)$ is 1.7 minutes. The mean time between transient failure $(1/\lambda_{tf}^d)$ is 8 hours. The average failure rate (λ_B^g) for each BR is once every $22,000$ hours. The expected repair time $(1/\mu_B)$ is 2 hours. The failure probability (c_2) for an idle BR is assumed to be $\lambda_B^g/(\lambda_B^g + \mu_B)$.

The grade of service (GOS) [11] is a measure of congestion, which is generally given as the probability of a call being blocked (for Erlang B) or as the probability of a call experiencing a delay greater than a certain queueing time (for Erlang C). Based on the blocking probabilities, we define the following:

- Light traffic: $GOS < 0.2\%$,
- Normal traffic: $0.2\% \leq GOS \leq 2\%$,
- Heavy traffic: $2\% < GOS$.

In the following, we compare the performance results between the recovery and the non-recovery methods under different traffic loads.

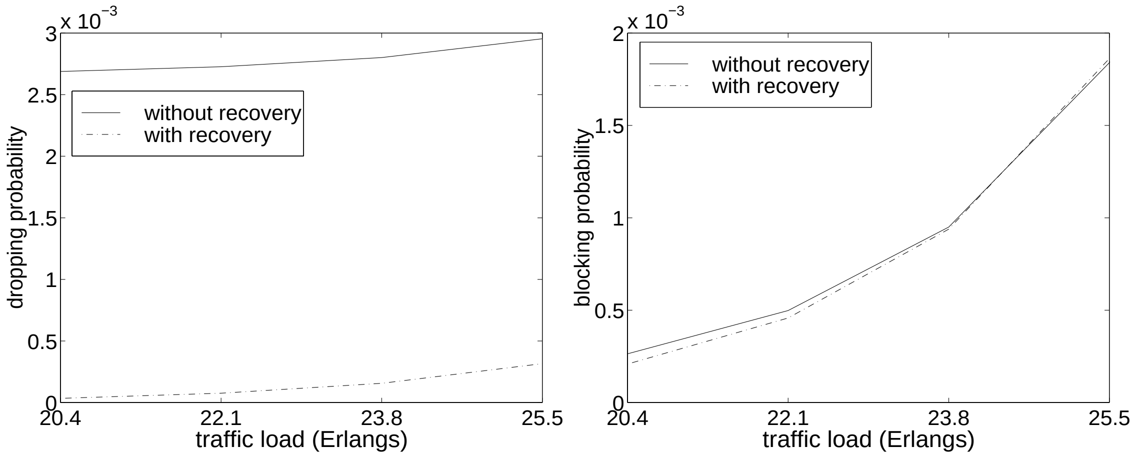

Fig. 8. Dropping/blocking probabilities under light traffic loads.

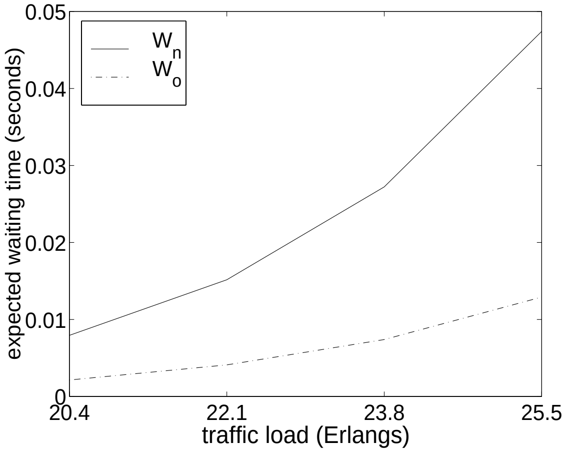

Fig. 9. The expected call waiting times for the recovery method under light traffic loads.

Light Traffic: When the traffic load is less and equal to 25.5 Erlangs, the network is undergoing light traffic (Figure 8). The recovery method reduces the dropped calls by at least 89.3%. For the original channel allocation algorithm without recoveries, any BR failure or transient failure may cause dropped calls. By using the channels which would be idle under the light traffic loads, we can reduce the dropping probabilities dramatically. Under most scenarios when the traffic is light, the blocked calls can be reduced as well. Because under light traffic, the probability of using idle channels for the retries (due to BR failure) of the new calls is much higher than the probability of assigning the idle channels to the new calls. Figure 9 shows the expected call waiting times for the recovery method under the light traffic loads. The restoration time is small enough that it is not detectable for the end users.

Normal Traffic: When the traffic load is between 27.2 and 32.3 Erlangs,

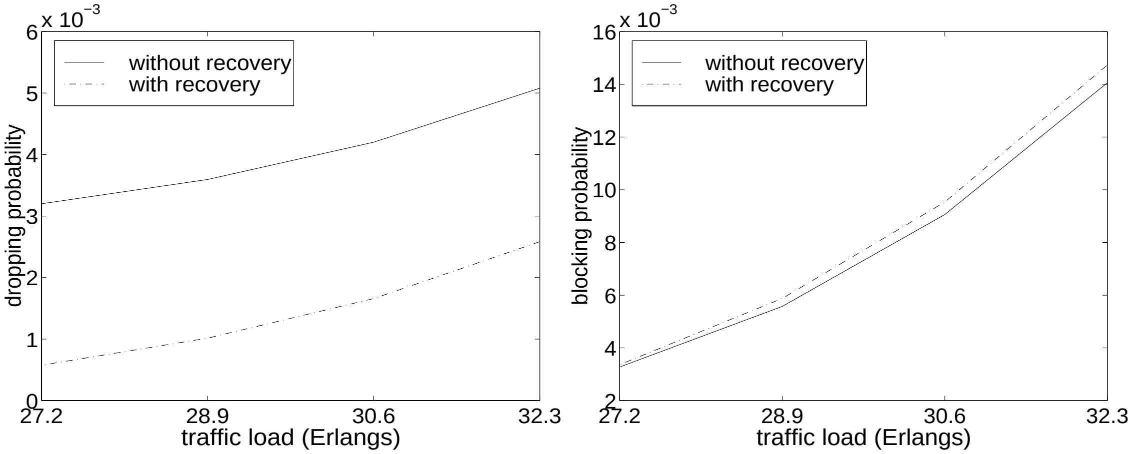

Fig. 10. Dropping/blocking probabilities under normal traffic loads.

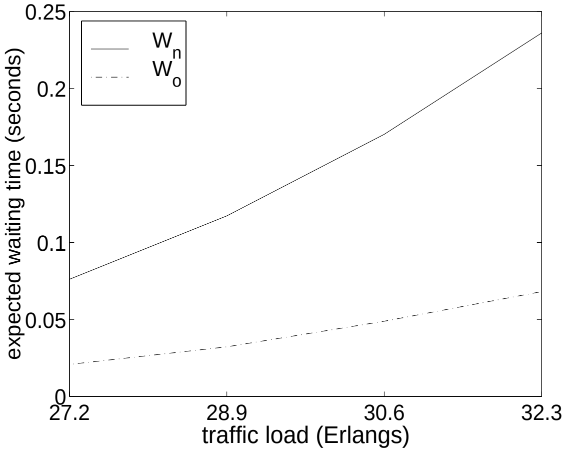

Fig. 11. The expected call waiting times for the recovery method under normal traffic loads.

the network is undergoing normal traffic (Figure 10). The dropped calls are reduced with an average of 65.86%. In the recovery method, some of the idle channels are used to recover the failed calls. In the non-recovery method, these channels might be used for accepting new calls. Consequently, the blocking probability might increase in the recovery scheme. Under normal traffic, this increase is fairly small, with an average of 4.52%. The recovery time for the ongoing calls (as shown in Figure 11) is less than 75 *ms*, which would be transparent to the end-users. As to the recovery times for the new calls, they are less than 250 *ms*. This belongs to part of the overhead in the call set up process, which is tolerable to the end users.

Heavy Traffic: The traffic is heavy (Figure 12) when the traffic load is above 32.3 Erlangs. The recovery method can still reduce the dropped calls by 19.37% when the traffic load is as high as 39.1 Erlangs. However, the expected call

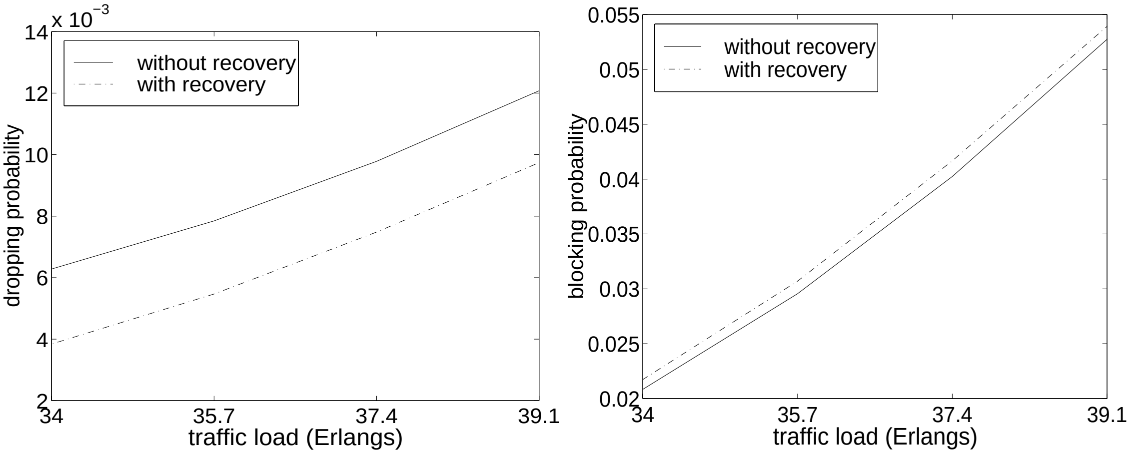

Fig. 12. Dropping/blocking probabilities under heavy traffic loads.

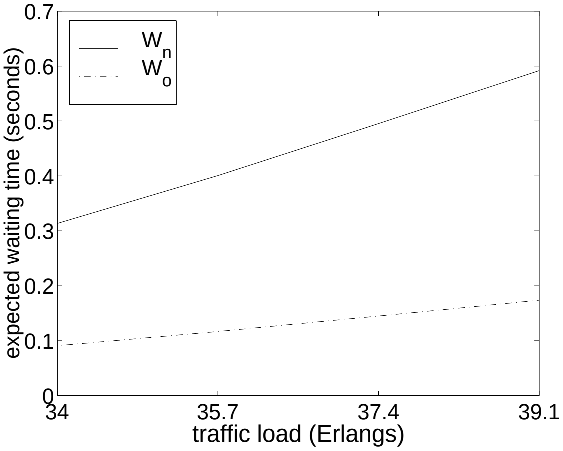

Fig. 13. The expected call waiting times for the recovery method under heavy traffic loads.

recovery time (Figure 13) for new calls would be around 600 ms, which is relatively high. In addition, under heavy traffic, the average blocking probability for the recovery method is 3.7%, which nearly doubles the generally accepted 2% standard. Therefore, increasing the bandwidth is highly recommended for enhancing the overall system performance when the traffic is heavy.

6 Conclusion

In this paper, a method for multiple channel recovery and the related algorithms of channel allocation with retries and repair are introduced for TDMA wireless communications systems. SRN models of the channel recovery method with repair process, and the original channel allocation method without recovery are developed. The results show that the recovery method can nearly eliminate dropped calls under light traffic. It can also dramatically reduce dropped calls under normal traffic. Even under heavy traffic, the method still improves the system performance by considerably decreasing the dropping probability. For heavily loaded wireless systems, increasing the bandwidth is recommended to operating companies for larger revenue, more profit, and improved customer satisfaction.

Since some of the idle channels which would otherwise be used for new calls are used to recover the failed ongoing calls, the blocking probability with the recovery scheme is increased in most situations, especially under normal and heavy traffic. This price is well justified. The numerical results indicate that with the recovery method, the dropped calls can be reduced significantly. At the same time, the blocked calls are increased insignificantly. In addition, from the numerical results, it is shown that the recovery times for the failed calls under light and normal traffic are nearly transparent to the end users.

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