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Load-balancing channel assignment for dual-band PCS networks

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Summary

This paper investigates the channel assignment problem of dual-band PCS systems where single-band and dual-band handsets co-exist. Load-balancing channel assignment schemes are proposed to improve the system performance. To balance the loads of both bands, the BSC selects a band to serve a call request of a dual-band handset based on the loads of both bands. In addition, a channel re-assignment scheme is used to further improve the system capacity. Analytic models and computer simulations have been developed to evaluate the performance of the load-balancing schemes. The results indicate that both load-balancing and channel re-assignment techniques significantly increase the system capacity as the percentage of dual-band handsets increases. Furthermore, the load-balancing with channel re-assignment scheme that combines both techniques achieves the best system performance even when the percentage of dual-band handset is as low as 25%. In addition, we describe an approach to reduce the signal overhead of the load-balancing schemes. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS
personal communications service (PCS)
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1. Introduction

Personal Communication Services (PCSs) have experienced an enormous growth during the last decade [1, 2]. The drive forces behind this growth is the reduction in the cost of handsets and service costs. Because of the enormous subscriber growth in most wireless networks, it becomes more and more important to provide sufficient network capacity. There are several techniques to enhance system capacity, such as microcells, half rate channels and dual-band systems [3, 4]. The microcell approach reduces the cell size and builds more base stations. As a result, the total number of channels and the system capacity increase. The microcell has a limitation on the cell size due to signal interference and dropped calls for fast moving mobiles [5, 6]. The implementation of half rate channels in a GSM mobile ratio network provides theoretically twice the network capacity of the full rate system. However, this capacity gain can only be achieved if mobile handsets support the half rate transmission. Dual-band systems increase radio channels by extending the radio bandwidth. A typical example is a dual-band GSM system which integrates GSM 900 and DCS 1800 [2, 7]. Since the GSM family shares the same network protocols, it is straightforward to integrate GSM 900 and DCS 1800 networks [4, 8]. In addition, dual-band handsets have become more popular to take advantage of the dual-band networks. The GSM family offering multi-band terminals and networks has become the popular digital standard of PCS [9, 10].

The carried traffic of a PCS network can be improved by using the techniques of dynamic channel assignment and channel re-assignment. Das *et al.* [11] proposed an efficient dynamic channel assignment scheme using channel borrowing between neighboring cells. They migrate channels through a structured borrowing mechanism to balance the loads of the cells. The results showed the scheme obtained a performance improvement of 12 per cent in terms of call blocking under moderate and heavy traffic conditions. Qiao *et al.* [12] proposed mobile relay stations within each cell to divert traffic in one cell to another. Their study indicated that the integration of the cellular and mobile/wireless relaying technologies can dynamically balance traffic between neighboring cells in a cellular system. Kuek and Wong [13] presented an ordered dynamic channel assignment with re-assignment scheme in microcells where a call connected to macrocells is re-assigned to microcells when channels in microcells become available.

Systems that employ microcells with overlaying macrocells to increase system capacity were proposed in Reference [14]. Rappaport and Hu [14] studied the performance of the overlaid network where new calls and handoff calls can enter at both cell levels. Ramsdale and Harrold [8] discussed a dual-band system where GSM 900 is deployed in normal cells to form a contiguous coverage layer and DCS 1800 is deployed in microcells as a different layer of discontinuous regions to enhance the capacity. A channel assignment scheme was developed to prevent high speed mobiles from using the radio channels of microcells. Rodriguez *et al.* [15] investigated the channel assignment problem of a dual cellular system supporting AMPS and D-AMPS. The subscribers use analog (AMPS) handsets or dual-mode (AMPS and D-AMPS) handsets, since each AMPS carrier can afford one analog channel or six digital channels. They proposed channel assignment schemes where dual-mode handsets use a digital channel whenever possible. Tegler *et al.* [4] analyzed the capacity improvement in the GSM/DCS dual-band system where all handsets are dual-band. Computer simulations were conducted to measure the maximum system capacity. Lai [16] studied the interconnection issues of dual-band GSM system. The study indicates that a homogeneous connection, where both GSM 900 and DCS 1800 share the same HLR, significantly outperforms a heterogeneous connection in the call incompletion probability.

However, the effects of the co-existence of dual-band and single-band handsets on the carried traffic have not been investigated. It is clear that as the percentage of dual-band handsets increases, the system carried traffic increases. In this paper, we will show that the channel re-assignment technique can significantly increase the carried traffic even when only 25 per cent of the handsets are dual-band. The effects of the user mobility on the system carried traffic will also be studied. In addition, the message overhead of the load-balancing schemes will be investigated. The paper is organized as follows. Section 2 presents dual-band PCS networks and channel assignment schemes. Section 3 describes analytic models for the channel assignment schemes. Section 4 derives equations for evaluating the system performance. Section 5 shows the analytic and simulation results. Section 6 concludes the paper.

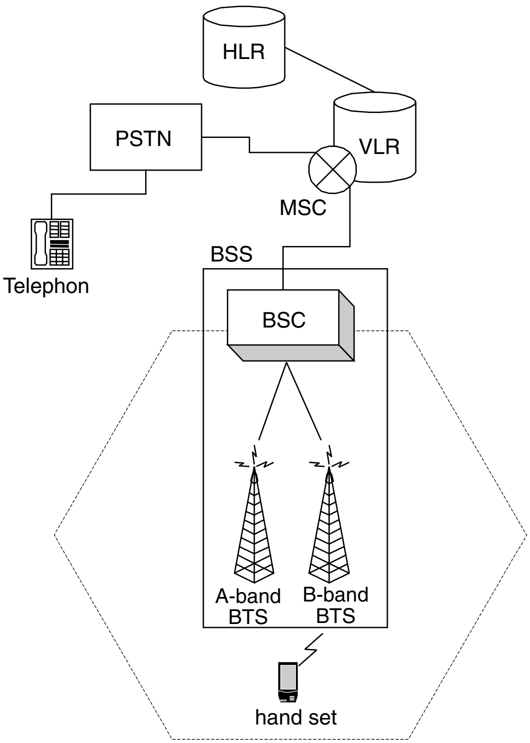


Fig. 1. The network architecture of dual-band systems.

2. Dual-Band PCS Networks and Channel Assignment

In Taiwan, dual-band GSM cellular networks have been provided by Chunghwa and Far EasTone Telecommunications. The networks consist of GSM900 and DCS1800 systems. In our study, we use A-band/B-band systems to represent dual-band PCS systems. Figure 1 shows the network architecture of a dual-band system. A base station subsystem (BSS) consists of a base station controller (BSC) and two base transceiver stations (BTS): an A-band BTS and a B-band BTS. The BSC connects to a mobile switching center (MSC), which connects to the switches of the public switched telephone network (PSTN) [17]. The BTS serves the calls to and from the handsets in its service area, called cells, via radio channels. The BSC assigns radio channels to serve the calls. To simplify the analytic model, we assume that an A-band cell and its overlaid B-band cell are of the same size and cover the same area. This configuration is a special case of the microcell/macrocell architecture where a macrocell overlays only one microcell [5, 6]. Since the A-band and B-band BTSs are located at the same site, one advantage of the overlaid architecture is cost reduction for site preparation and site rental.

A home location register (HLR) and visitor location registers (VLRs) facilitate the roaming management of handsets. One or more cells are grouped to form a registration area. The BSCs of a registration area are connected to an MSC providing the call processing for all the handsets within the service area. Every registration area has a corresponding VLR which keeps a record for each handset visiting the registration area. The HLR contains the primary information of each handset, including the visited VLR of the handset. In this way, the current location of a handset can be obtained from the HLR. For the dual-band handsets, the dual-band network configuration can be considered as a single network where the radio spectrum has been extended from one band to two bands [16]. However, a dual-band handset tunes to only one of the BTSs. When a dual-band handset requests a channel, the BSC assigns a free channel from the BTS to which the dual-band handset is tuning.

2.1. The load-balancing scheme

Since a dual-band handset can use the channels of either band. This flexibility can be utilized to balance the loads of both bands. Based on the numbers of free channels on both bands and the expected loads of both bands, the BSC selects a band to serve a call of a dual-band handset. The goal of this band-selection is to balance the loads of both bands and to minimize the probability that a call cannot be completed (either be blocked or forced to terminate for no free channels).

For load-balancing, a simple, greedy algorithm for band-selection may assign the band with a greater number of free channels to serve a call request of a dual-band handset. However, this greedy algorithm may not balance the loads of both bands in the long

```
C_R = C_A + 0.5;   /* all dual-band handsets use B-band */
C_L = -C_B - 0.5;  /* all dual-band handsets use A-band */
while C_R-C_L>ε do   /* ε is a pre-defined small value */
        C_1 = (C_L+C_R)/2;
        C_2 = C_1 + ε_1;   /* ε_1 is a pre-defined small value */
        if P_nc(C_1) > P_nc(C_2)
              C_L = C_1;
        else
              C_R = C_2;
        endif
endwhile
C_min = C_R or C_L;
```

Fig. 2. The pseudo code of the bisection search algorithm to determine $C_{\min}$.

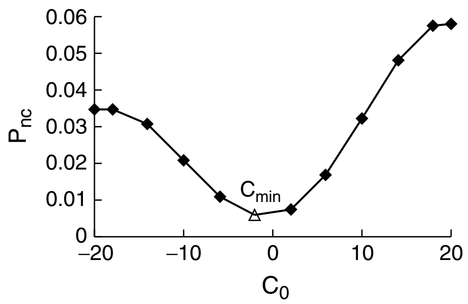


Fig. 3. The effects of band-selection parameter C_0 on P_{nc}.

run, because the expected load of A-band (single-band) handsets and that of B-band handsets may be unequal. Our algorithm selects a serving band to balance the loads in the long term, and thus minimize the call probability that a call is incompleted.

The band-selection algorithm works as follows. Let F_A denote the number of free channels in the A-band, F_B denote that of the B-band, and $D = F_A - F_B$. A bisection search algorithm [18] that will be presented in Figure 2 determines a band-selection parameter $C_0 = C + f$ where C is an integer and $-0.5 < f \leq 0.5$; the numbers are used by the band-selection algorithm. For a call request of a dual-band handset, if $D > C$, A-band is selected to serve the request; If $D < C$, B-band is selected. If $D = C$, A-band is selected with probability $f + 0.5$ and B-band with probability $0.5 - f$. Note that when $D = C$ and $f = 0$, half of the dual-band handsets are served by the A-band. For a given C_0, the call incompletion probability (P_{nc}) can be obtained using an iterative algorithm described in Section 4.5, i.e., P_{nc} can be expressed as a function of C_0. The function is a concave upward curve as shown in Figure 3. Consider the curve where $C_0 < C_{\min}$. If C_0 is decreased, P_{nc} increases because the traffic loads in both bands become more unbalanced. This is also true when $C_0 > C_{\min}$ and C_0 is increased. There exists an optimal value of C_0 such that P_{nc} can be minimized. A bisection search algorithm, described in Reference [18], can be used to obtain the optimal value, $C_{\min}$. The pseudo code is listed as follows. In this algorithm, C_A (C_B) is the channel capacity of A-band (B-band) in a cell.

To originate a call, a dual-band handset uses the signaling channel to send the call attempt. Then, the BSC instructs the handset to use the selected serving band. Second, for call termination, the BSC asks the BTSs of both bands to page the dual-band handset. Then, the dual-band handset requests an idle channel from the BSC. If the requested band is not the selected serving band, the BSC instructs the handset to switch to the other band and to request an idle channel. The detailed message flows of GSM systems are described as follows.

Figure 4 shows the message flows of call termination for a dual-band handset in dual-band GSM systems [19]. This example illustrates that a handset tunes to BTS-A and switches over to BTS-B on call termination to the handset.

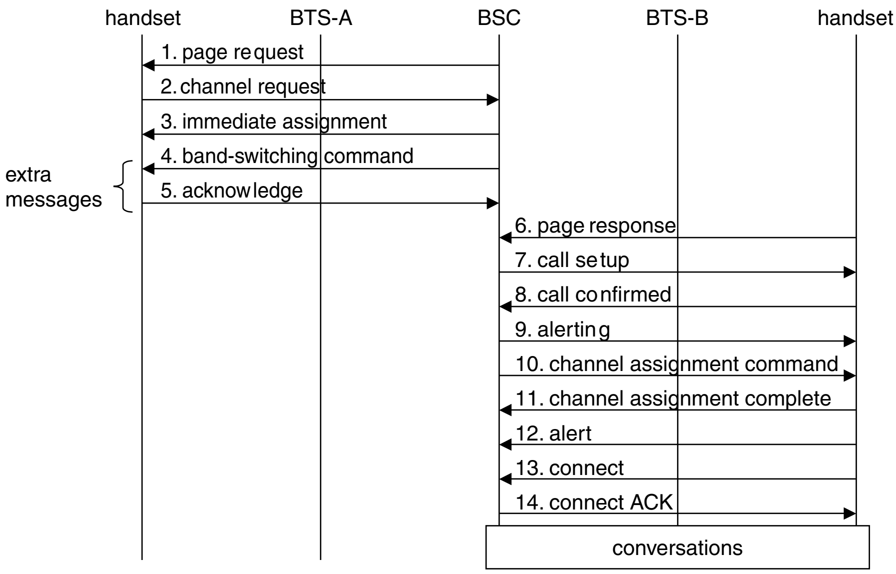


Fig. 4. The message flows of call termination for a dual-band handset with band-switching.

Step 1: The handset tunes to BTS-A. The BSC sends a page request through both BTSs to the handset.

Step 2: On receiving the page request, the handset sends a channel request to the BSC.

Step 3: After receiving the channel request message, the BSC allocates a message communication channel (SDCCH: Stand-alone Dedicated Control CHannel) and sends an immediate assignment message to the handset. The handset communicates with the BSC over the SDCCH until a voice channel is assigned [19].

Steps 4 & 5: The BSC sends a band-switching command to the handset over the SDCCH. The handset sends an acknowledge back to the BSC and switches to B-band.

Step 6: The handset tunes to BTS-B. Then, it sends a page response to the BSC.

Steps 7–14: The handset and BSC follow the GSM protocol to set up a call connection [19].

Note that Steps 4 and 5 are the additional message exchanges for the band-switching; other steps are the message exchanges for a normal call termination. Thus, the message overhead of the band-switching on call termination to a handset is two extra messages.

In this scheme, the BSC must be capable of determining the selected serving band and instructing dual-band handsets to switch over to the other band on call origination and call termination. However, for a handoff call, the dual-band handset tries to use the same band as it uses in the old cell. If no free channel is available, it is forced to terminate. This scheme will be referred to as the Load-Balancing (LB) scheme.

2.2. The load-balancing scheme with inter-band handoff

To improve the LB scheme, the handoff calls of dual-band handsets are instructed to switch to the selected serving band. The procedures of call origination and call termination are the same as those in the LB scheme. This scheme will be referred to as the Load-Balancing scheme with Inter-band Handoff (LBIH). Figure 5 shows the message flows of an Inter-BSC handover call of a dual-band handset that switches to the selected serving band in the new cell. The example is a dual-band GSM system where the two BSCs connect to the same MSC.

Step 1: Before a dual-band call is handed over to a new cell, the MSC requests a channel for the dual-band handset in the new cell.

Step 2: BTS-B allocates a new channel and sends a channel request acknowledge to the MSC.

Step 3: The MSC sends a handover command to the handset on the FACCH (Fast Associated Control CHannel). The channel ID of the handover command indicates that band-switching is required.

Steps 4–9: The handset and BTSs follow the GSM protocol to hand the call over to BTS-B.

Note that Step 3 combines a handover command and a band-switching command in one message.

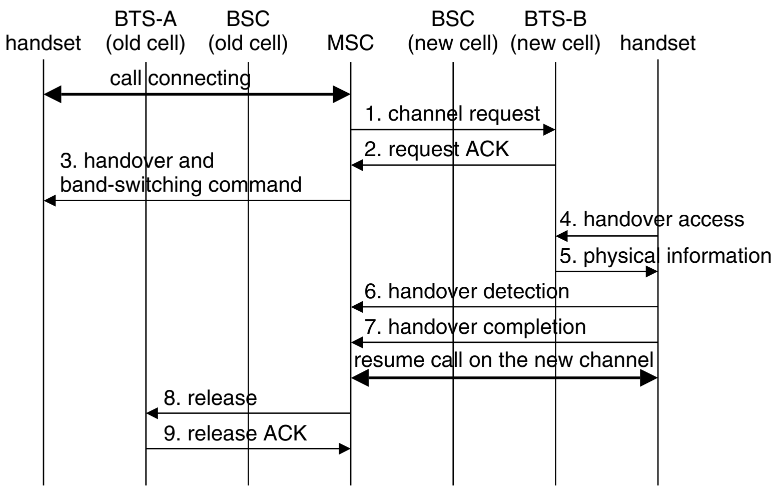


Fig. 5. The message flows of a handover call with band-switching for dual-band handsets.

Therefore, no extra message exchange is required for this inter-band handoff.

2.3. The load-balancing with channel re-assignment

In the two schemes described above, an initial call or a handoff call of an A-band handset is blocked if there is no free channel at A-band. However, the call can be still connected if a dual-band handset using an A-band channel can be re-assigned to a free channel at the B-band. The released A-band channel can serve the request of the A-band handset. The channel re-assignment technique has been studied in References [12, 13]. By using this channel re-assignment technique, a call of an A-band handset will be rejected only if all A-band channels are assigned to A-band handsets or there is no free channel at both bands. The same channel re-assignment technique can also be applied to B-band handsets.

The channel re-assignment procedure works as follows. First, to originate a call, a single-band handset uses the signaling channel to make a call attempt. If the corresponding BTS has no free channel and some busy channels are used by the dual-band users, the BSC selects a victim from the dual-band handsets. The BSC then selects an idle channel from the other BTS and uses the signaling channel to inform the victim to switch to the other band. The victim releases the original channel and resumes the call on the selected channel. The BSC then uses the signaling channel to instruct the single-band handset to tune to the released channel. Second, for call termination, the BSC asks the corresponding BTS to page the single-band handset. The BSC then selects a dual-band handset victim, re-assigns the victim to a free channel of the other BTS, and instructs the single-band handset to tune to the released channel. Last, for a handoff call, the handset initiates the handoff procedure by sending signals to the new BSC. The BSC selects a dual-band handset victim to release its channel and re-assigns a free channel from the other BTS. Then, the BSC notifies the MSC to set up a new routing path, and the single-band handset is handed over to the released channel in the new BTS. This channel re-assignment scheme will be referred to as the Load-Balancing with Channel Re-assignment (LBCR).

The overhead of a channel re-assignment is to force a dual-band handset to switch over to the other BTS of the same cell. This band-switching procedure is the same as an inter-BTS handoff procedure in a single-band system. The message flows of an inter-BTS handoff can be found in References [20, 21].

2.4. Reduce the overhead

Band-switching on call origination and call termination for a dual-band handset requires extra message exchanges, which may result in congestion on the signal channels. The message overhead can be reduced if fewer band-switchings are performed. For example, when the system traffic load is low, a band-switching is unnecessary because there are many free channels at both bands. Therefore, we can reduce the message overhead if band-switching is performed only when the traffic load is larger than a threshold t. The threshold t will be referred to as the band-switching threshold. On the other hand, since the band-switching of a dual-band handover call requires no message overhead, this band-switching is always performed.

3. Analytic Models

In this section, an analytic model using a four-dimensional Markov chain is developed to evaluate the load-balancing schemes [14, 22]. We assume that A-band and B-band BTS are co-siting. This setup is actually exercised in GSM networks in Taiwan. An A-band cell and its overlay B-band cell are assumed to be of the same size and cover the same area. Furthermore, we assumed cells in the system are homogeneous, i.e., all cells have the same traffic load.

The terms and parameters used in our model are described as follows:

- λ_A (λ_B, λ_{db}): the call arrival rate of A-band handsets (B-band handsets, dual-band handsets) in a cell; the call arrivals are assumed to be a Poisson process.
- $1/\mu$: the mean call holding time. We assume that the call holding time has a negative exponential distribution with mean $1/\mu$ as suggested in References [22, 23].
- $1/\eta$: the mean cell residence time of a handset at a cell. We assume that the cell residence time has a negative exponential distribution with mean $1/\eta$.
- λ_{A_h} (λ_{B_h}, λ_{db_h}): the handoff call arrival rate of A-band handsets (B-band handsets, dual-band handsets) to a cell; the handoff call arrivals of A-band and B-band handsets are assumed to be a Poisson process.

- $\lambda_{db\_h\_A}$ ($\lambda_{db\_h\_B}$): the handoff call arrival rate to a cell for the dual-band users connecting an A-band (B-band) channel in the previous cell; the handoff call arrivals are assumed to be a Poisson process.
- λ_{db_A} (λ_{db_B}): The call arrival rate of dual-band handsets tuning to A-band (B-band); the call arrivals are assumed to be a Poisson process.
- $S(i, j, k, l)$: the state of a cell, where i represents the number of active A-band handsets, j represents the number of active B-band handsets, k represents the number of dual-band handsets using A-band channels, and l represents the number of dual-band handsets using B-band channels in the cell.

3.1. State transitions of the LB scheme

Figure 6 depicts the state transitions around $S(i, j, k, l)$ for the LB scheme. Note that a legal state $S(i, j, k, l)$ must satisfy $0 \le i + k \le C_A$ and $0 \le j + l \le C_B$. The state transitions can be summarized as follows.

(1) When an A-band user (B-band user) initiates a call with rate λ_A (λ_B) or an A-band user (B-band user) handoff call arrives with rate λ_{A_h} (λ_{B_h}), the state parameter i (j) is incremented by 1, i.e., a free channel of A-band (B-band) is assigned to serve the call.

(2) When an A-band (B-band) call terminates with rate μ or leaves the cell with rate η, the state parameter i (j) is decremented by 1, i.e., a free channel of A-band (B-band) is released.

(3) When a dual-band user initiates a call with rate λ_{db} and $D > C$ ($D < C$), the state parameter k (l) is incremented by 1. If $D = C$, A-band is selected with probability $f + 0.5$ and B-band is selected with probability $0.5 - f$. On the other hand, when a dual-band handoff call using an A-band (B-band) channel arrives with rate $\lambda_{db\_h\_A}$ ($\lambda_{db\_h\_B}$), the state parameter k (l) is incremented by 1 because handoff calls always use the same band. Let $D_A[i, j, k, l]$ be the transition rate from $S(i, j, k, l)$ to $S(i, j, k+1, l)$ and $D_B[i, j, k, l]$ be the transition rate from $S(i, j, k, l)$ to $S(i, j, k, l+1)$. The state transitions can be expressed as follows,

$$D_A[i, j, k, l] = \begin{cases} \lambda_{db} + \lambda_{db\_h\_A}, & \text{if } D > C \\ \lambda_{db\_h\_A}, & \text{if } D < C \\ (\lambda_{db} + \lambda_{db\_h})(f + 0.5) & \text{if } D = C \end{cases}$$

$$D_B[i, j, k, l] = \begin{cases} \lambda_{db} + \lambda_{db\_h\_B}, & \text{if } D < C \\ \lambda_{db\_h\_B}, & \text{if } D > C \\ (\lambda_{db} + \lambda_{db\_h})(0.5 - f) & \text{if } D = C \end{cases}$$

(4) When a dual-band call using an A-band (B-band) channel terminates with rate μ or leaves the cell with rate η, the state parameter k (l) is decremented by 1.

3.2. State transitions of the LBIH scheme

The state transition diagram of the LBIH scheme is similar to that of the LB scheme. The difference between them is the channel assignment for the handoff calls of dual-band handsets. For a handoff call of a dual-band handset, the LBIH scheme assigns a channel from the selected serving band to the call; the LB scheme assigns a channel from the same band serving the call in the old cell.

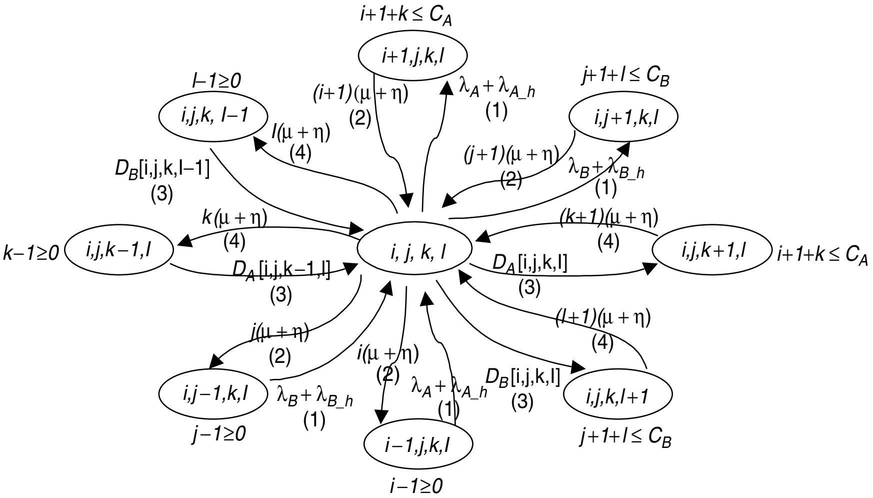


Fig. 6. State transitions around $S(i, j, k, l)$ for the LB scheme.

(1) The state transitions corresponding to single-band user events are the same as those in the LB scheme.
(2) The state transitions for dual-band user events including terminating a call and leaving a cell are the same as those in the LB scheme.
(3) When a dual-band user initializes a call with rate λ_{db} or a dual-band call is handed over with rate $\lambda_{db\_h\_A} + \lambda_{db\_h\_B}$, the state parameter k (l) is incremented by 1, if $D > C$ ($D < C$). If $D = C$, A-band is selected with probability $f + 0.5$ and B-band is selected with probability $0.5 - f$. Transition rates $D_A[i, j, k, l]$ and $D_B[i, j, k, l]$ shown in Figure 7 can be expressed as follows,

$$D_A[i, j, k, l] = \begin{cases} \lambda_{db} + \lambda_{db\_h}, & \text{if } D > C \\ 0, & \text{if } D < C \\ (\lambda_{db} + \lambda_{db\_h})(f + 0.5) & \text{if } D = C \end{cases}$$

$$D_B[i, j, k, l] = \begin{cases} \lambda_{db} + \lambda_{db\_h}, & \text{if } D < C \\ 0, & \text{if } D > C \\ (\lambda_{db} + \lambda_{db\_h})(0.5 - f) & \text{if } D = C \end{cases}$$

3.3. State transitions of the LBCR scheme

The Markov chain of the LBCR scheme can be simplified to a three-dimensional model as shown

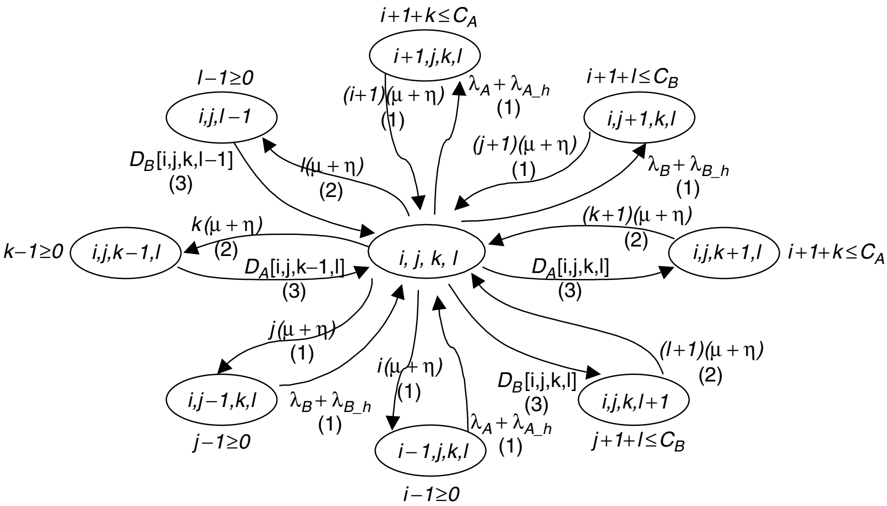


Fig. 7. State transitions around $S(i, j, k, l)$ for the LBIH scheme.

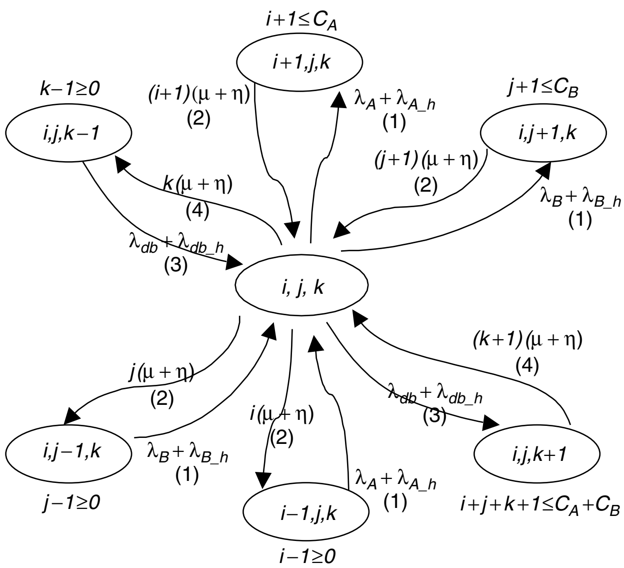


Fig. 8. State transitions around $S(i, j, k)$ for the LBCR scheme.

in Figure 8. $S(i, j, k)$ denotes the state for a cell, where i represents the number of active A-band handsets, j represents the number of active B-band handsets, and k represents the number of active dual-band handsets. Figure 8 depicts the state transitions around $S(i, j, k)$. Note that a legal state $S(i, j, k)$ must satisfy $0 \le i \le C_A$, $0 \le j \le C_B$ and $0 \le i + j + k \le C_A + C_B$. The state transitions can be described as follows.

(1) When an A-band user (B-band user) initiates a call with rate λ_A (λ_B) or an A-band user (B-band user) handoff call arrives with rate λ_{A_h} (λ_{B_h}), the state parameter i (j) is incremented by 1.
(2) When an A-band (B-band) call terminates with rate μ or leaves the cell with rate η, the state parameter i (j) is decremented by 1.
(3) When a dual-band user initiates a call with rate λ_{db}, the state parameter k is incremented by 1.
(4) When a dual-band call terminates with rate μ or leaves the cell with rate η, the state parameter k is decremented by 1.

4. Performance Analysis

To evaluate the system performance, the following terms are defined.

- $\pi_{i,j,k,l}$: the steady state probability of the state $S(i, j, k, l)$.
- $R_{\text{out}}(i, j, k, l)$ ($R_{\text{in}}(i, j, k, l)$): the net outgoing (incoming) flow rate of state $S(i, j, k, l)$.
- P_0: the probability that a new call is blocked (the average of A-band, B-band and dual-band handsets).
- P_{A_0} (P_{B_0}, P_{db_0}): the new call blocking probability of A-band (B-band, dual-band) handsets.
- P_f: the probability that a call is forced to terminate.
- P_{A_f} (P_{B_f}, P_{db_f}): the forced termination probability of A-band (B-band, dual-band) handsets.
- P_{nc}: the probability that a call is not completed (either blocked or forced to terminate).
- P_{A_nc} (P_{B_nc}, P_{db_nc}): the call-incompletion probability of A-band (B-band, dual-band) users.
- P_{bs} (R_{bs}): the probability (rate) that on call origination or call termination, a dual-band handset needs to switch to the band with more free channels.
- P_{hs} (R_{hs}): the probability (rate) that a handoff call of a dual-band handset needs to switch to the band with more free channels.
- P_{fs} (R_{fs}): the probability (rate) that call origination or call termination of a single-band handset forces a dual-band call to switch to the other band.

Since the sum of the all steady state probabilities is equal to 1, we have

$$\sum_{i,j,k,l} \pi_{i,j,k,l} = 1 \tag{1}$$

Since the system is in a steady state, the net outgoing flow rate and the net incoming flow rate are equal for all states. We have

$$R_{\text{out}}(i, j, k, l) = R_{\text{in}}(i, j, k, l), \text{ for all legal states } S(i, j, k, l). \tag{2}$$

From the balanced Equations (1) and (2), we can derive the steady state probabilities of all states $\pi_{i,j,k,l}$.

The dual-band handoff rate λ_{db_h} can be derived using the iterative algorithm described in Section 4.5. We can calculate $\lambda_{db\_h\_A}$ and $\lambda_{db\_h\_B}$ using the following equations.

$$\lambda_{db\_h\_A} = \lambda_{db\_h} \frac{\sum_{i=0}^{C_A}\sum_{j=0}^{C_B}\sum_{k=0}^{C_{A-i}}\sum_{l=0,k+l\neq 0}^{C_{B-j}} \frac{k}{k+l}\pi_{i,j,k,l}}{1 - \sum_{i=0}^{C_A}\sum_{j=0}^{C_B}\pi_{i,j,0,0}}$$

$$\lambda_{db\_h\_B} = \lambda_{db\_h} \frac{\sum_{i=0}^{C_A}\sum_{j=0}^{C_B}\sum_{k=0}^{C_{A-i}}\sum_{l=0,k+l\neq 0}^{C_{B-j}} \frac{l}{k+l}\pi_{i,j,k,l}}{1 - \sum_{i=0}^{C_A}\sum_{j=0}^{C_B}\pi_{i,j,0,0}} \tag{3}$$

Since the number of the dual-band handsets tuning to A-band (B-band) is proportional to the number of the dual-band handsets using A-band (B-band) channel. Therefore, the call arrival rates λ_{db_A} and λ_{db_B} can be expressed as

$$\lambda_{db\_A} = \lambda_{db} \frac{\sum_{i=0}^{C_A}\sum_{j=0}^{C_B}\sum_{k=0}^{C_{A-i}}\sum_{l=0,k+l\neq 0}^{C_{B-j}} \frac{k}{k+l}\pi_{i,j,k,l}}{1 - \sum_{i=0}^{C_A}\sum_{j=0}^{C_B}\pi_{i,j,0,0}}$$

$$\lambda_{db\_B} = \lambda_{db} \frac{\sum_{i=0}^{C_A}\sum_{j=0}^{C_B}\sum_{k=0}^{C_{A-i}}\sum_{l=0,k+l\neq 0}^{C_{B-j}} \frac{l}{k+l}\pi_{i,j,k,l}}{1 - \sum_{i=0}^{C_A}\sum_{j=0}^{C_B}\pi_{i,j,0,0}} \tag{4}$$

4.1. The LB scheme

In the LB scheme, an A-band user call is blocked or forced to terminate if no free A-band channel is available. We have

$$P_{A\_0} = P_{A\_f} = \sum_{j,l,i+k=C_A} \pi_{i,j,k,l}$$

Similarly, the new call blocking and forced termination probabilities of B-band users can be expressed as

$$P_{B\_0} = P_{B\_f} = \sum_{i,k,j+l=C_B} \pi_{i,j,k,l}$$

A dual-band user call request is blocked if no available A-band or B-band channel. The new call blocking probability of dual-band user can be expressed as

$$P_{db\_0} = \sum_{i+k=C_A \text{ and } j+l=C_B} \pi_{i,j,k,l}$$

The new call blocking probability can be expressed as

$$P_0 = \frac{\lambda_A}{\lambda_A + \lambda_B + \lambda_{db}} P_{A\_0} + \frac{\lambda_B}{\lambda_A + \lambda_B + \lambda_{db}} P_{B\_0} + \frac{\lambda_{db}}{\lambda_A + \lambda_B + \lambda_{db}} P_{db\_0} \quad (5)$$

A handoff call of a dual-band user using an A-band channel (B-band channel) is forced to terminate if no free A-band channel (B-band channel) in the cell where the call is handed over. We have

$$P_{db\_A\_f} = \sum_{j,l,i+k=C_A} \pi_{i,j,k,l}$$

$$P_{db\_B\_f} = \sum_{i,k,j+l=C_B} \pi_{i,j,k,l}$$

The forced termination probability of dual-band users can be expressed as

$$P_{db\_f} = \frac{\lambda_{db\_h\_A}}{\lambda_{db\_h}} \sum_{j,l,i+k=C_A} \pi_{i,j,k,l} + \frac{\lambda_{db\_h\_B}}{\lambda_{db\_h}} \sum_{i,k,j+l=C_B} \pi_{i,j,k,l}$$

The forced termination probability of all users can be written as

$$P_f = \frac{\lambda_{A\_h}}{\lambda_{A\_h} + \lambda_{B\_h} + \lambda_{db\_h}} P_{A\_f} + \frac{\lambda_{B\_h}}{\lambda_{A\_h} + \lambda_{B\_h} + \lambda_{db\_h}} P_{B\_f} + \frac{\lambda_{db\_h}}{\lambda_{A\_h} + \lambda_{B\_h} + \lambda_{db\_h}} P_{db\_f} \quad (6)$$

We can obtain the call-incompletion probability P_{nc} using the equation developed in Reference [24],

$$P_{nc} = P_0 + \left(\frac{\lambda_h}{\lambda}\right) P_f, \quad (7)$$

where $\lambda = \lambda_A + \lambda_B + \lambda_{db}$ and $\lambda_h = \lambda_{A\_h} + \lambda_{B\_h} + \lambda_{db\_h}$.

4.2. The LBIH scheme

In the LBIH scheme, an A-band (B-band) user call is blocked or forced to terminate if no free A-band (B-band) channel is available. We have

$$P_{A\_0} = P_{A\_f} = \sum_{j,l,i+k=C_A} \pi_{i,j,k,l}$$

$$P_{B\_0} = P_{B\_f} = \sum_{i,k,j+l=C_B} \pi_{i,j,k,l}$$

A dual-band user call request is blocked or forced to terminate if there is no available A-band or B-band channel. We have

$$P_{db\_0} = P_{db\_f} = \sum_{i+k=C_A \text{ and } j+l=C_B} \pi_{i,j,k,l}$$

The new call blocking, forced termination, and call-incompletion probabilities can be obtained from Equations (5), (6), and (7).

4.3. The LBCR scheme

In the LBCR scheme, an A-band (B-band) user call is blocked or forced to terminate if no free A-band (B-band) channel is available or no free A-band or B-band channel is available. We have

$$P_{A\_0} = P_{A\_f} = \sum_{i=C_A \text{ or } i+j+k=C_A+C_B} \pi_{i,j,k}$$

$$P_{B\_0} = P_{B\_f} = \sum_{j=C_B \text{ or } i+j+k=C_A+C_B} \pi_{i,j,k}$$

A dual-band user call request is blocked or forced to terminate if no available A-band or B-band channel. We have

$$P_{db\_0} = P_{db\_f} = \sum_{i+j+k=C_A+C_B} \pi_{i,j,k}$$

The new call blocking, forced termination, and call-incompletion probabilities can be obtained from Equations (5), (6), and (7).

4.4. The overhead

If $D > C$, a dual-band handset tuning to B-band needs to switch to A-band on call origination or call termination. P_{bs} and R_{bs} can be expressed as

$$P_{bs} = \left(\frac{\lambda_{db\_A}}{\lambda_{db}}\right) \sum_{(C_A-i-k)-(C_B-j-l)<C} \pi_{i,j,k,l} + \left(\frac{\lambda_{db\_B}}{\lambda_{db}}\right) \sum_{(C_A-i-k)-(C_B-j-l)>C} \pi_{i,j,k,l}$$

$$R_{bs} = \lambda_{db\_A} \sum_{(C_A-i-k)-(C_B-j-l)<C} \pi_{i,j,k,l} + \lambda_{db\_B} \sum_{(C_A-i-k)-(C_B-j-l)>C} \pi_{i,j,k,l}$$

On the channel request of a single-band handset, if there is no free channel in the requested band, an active dual-band handset tuning to the band is selected and forced to switch to the other band. P_{fs} and R_{fs} can be expressed as

$$P_{fs} = \left(\frac{\lambda_A + \lambda_{A\_h}}{\lambda_A + \lambda_B + \lambda_{A\_h} + \lambda_{B\_h}}\right) \times \left(\sum_{i+k=C_A, j+l<C_B, k>0} \pi_{i,j,k,l}\right) + \left(\frac{\lambda_B + \lambda_{B\_h}}{\lambda_A + \lambda_B + \lambda_{A\_h} + \lambda_{B\_h}}\right) \times \left(\sum_{j+l=C_B, i+k<C_A, l>0} \pi_{i,j,k,l}\right)$$

$$R_{fs} = (\lambda_A + \lambda_{A\_h}) \left(\sum_{i+k=C_A, j+l<C_B, k>0} \pi_{i,j,k,l}\right) + (\lambda_B + \lambda_{B\_h}) \left(\sum_{j+l=C_B, i+k<C_A, l>0} \pi_{i,j,k,l}\right)$$

Using the band-switching threshold described in Section 2.4, we can reduce the number of band-switchings performed on call origination and call termination of dual-band handsets. For a band-switching threshold t, band-switching is performed when the load of a BTS is large than t. The probability P_{bs} and the rate R_{bs} can be expressed as

$$P_{bs} = \left(\frac{\lambda_{db\_A}}{\lambda_{db}}\right) \times \left(\sum_{(i+k>t) \text{ and } ((C_A-i-k)-(C_B-j-l)<C)} \pi_{i,j,k,l}\right) + \left(\frac{\lambda_{db\_B}}{\lambda_{db}}\right) \times \left(\sum_{(j+l>t) \text{ and } ((C_A-i-k)-(C_B-j-l)>C)} \pi_{i,j,k,l}\right)$$

$$R_{bs} = \lambda_{db\_A} \times \left(\sum_{(i+k>t) \text{ and } ((C_A-i-k)-(C_B-j-l)<C)} \pi_{i,j,k,l}\right) + \lambda_{db\_B} \times \left(\sum_{(j+l>t) \text{ and } ((C_A-i-k)-(C_B-j-l)>C)} \pi_{i,j,k,l}\right)$$

4.5. An iterative algorithm

We can use an iterative algorithm, proposed by Hong and Rappaport [23], to calculate new call blocking and forced termination probabilities. Let P_{n0} be the probability that a new call at the cell is not completed before the handset moves out of the cell, and P_{nh} be the probability that a handoff call at a cell is not completed before the handset moves out of the cell. We have

$$P_{n0} = P_{nh} = \int_{t=0}^{\infty} \int_{t_c=t}^{\infty} \eta e^{-\eta t} \mu e^{-\mu t_c} \mathrm{d}t_c \mathrm{d}t = \frac{\eta}{\mu + \eta} \quad (8)$$

Consider the LB scheme, the handoff rate of A-band handsets can be expressed as

$$\lambda_{A\_h} = \lambda_A(1 - P_{A\_0})P_{n0} + \lambda_{A\_h}(1 - P_{A\_f})P_{nh} \quad (9)$$

Equation (9) indicates that handoff calls of A-band handsets occur in two cases:

- A new call of A-band handsets is not blocked with rate $\lambda_A(1 - P_{A\_0})$. In addition, the call is not completed before it moves out of the cell with probability P_{n0}.
- A handoff call of A-band handsets is not forced to terminate with rate $\lambda_{A\_h}(1 - P_{A\_f})$. In addition, the call is not completed before it moves out of the cell with probability P_{nh}.

From Equations (8) and (9), we have

$$\lambda_{A\_h} = \frac{\eta\lambda_A(1 - P_{A\_0})}{\mu + \eta P_{A\_f}} \quad (10)$$

Similarly, the handoff rate of B-band handsets can be written as

$$\lambda_{B\_h} = \frac{\eta\lambda_B(1 - P_{B\_0})}{\mu + \eta P_{B\_f}} \tag{11}$$

Consider the handoff rate of dual-band handsets connecting A-band channels in the previous cell. We have

$$\lambda_{db\_h\_A} = \lambda_{db}(1 - P_{db\_0})P_{n0} + \lambda_{db\_h\_A}(1 - P_{db\_A\_f})P_{nh} \tag{12}$$

From Equations (8) and (12), we obtain

$$\lambda_{db\_h\_A} = \frac{\eta\lambda_{db}(1 - P_{db\_0})}{\mu + \eta P_{db\_A\_f}} \tag{13}$$

Similarly, we have

$$\lambda_{db\_h\_B} = \frac{\eta\lambda_{db}(1 - P_{db\_0})}{\mu + \eta P_{db\_B\_f}} \tag{14}$$

From Equations (13) and (14), we obtain

$$\lambda_{db\_h} = \frac{\eta\lambda_{db}(1 - P_{db\_0})}{\mu + \eta P_{db\_A\_f}} + \frac{\eta\lambda_{db}(1 - P_{db\_0})}{\mu + \eta P_{db\_B\_f}} \tag{15}$$

For the LBIH and LBCR schemes, the handoff rates of A-band and B-band handsets can also be calculated using Equations (10) and (11). The handoff rate of dual-band handsets can be expressed as

$$\lambda_{db\_h} = \lambda_{db}(1 - P_{db\_0})P_{n0} + \lambda_{db\_h}(1 - P_{db\_f})P_{nh} \tag{16}$$

From Equations (8) and (16), we can get

$$\lambda_{db\_h} = \frac{\eta\lambda_{db}(1 - P_{db\_0})}{\mu + \eta P_{db\_f}} \tag{17}$$

We can calculate new call blocking and forced termination probabilities, using the following iterative algorithm.

Step 1. Select initial values for λ_{A_h}, λ_{B_h}, and λ_{db_h}.

Step 2. Compute P_{A_0}, P_{B_0}, P_{db_0}, P_{A_f}, P_{B_f}, and P_{db_f} using equations derived in the previous sections.

Step 3. Let $\lambda_{A\_h,\text{old}} \leftarrow \lambda_{A\_h}$, $\lambda_{B\_h,\text{old}} \leftarrow \lambda_{B\_h}$, and $\lambda_{db\_h,\text{old}} \leftarrow \lambda_{db\_h}$

Step 4. Compute the handoff rates λ_{A_h}, λ_{B_h}, and λ_{db_h} by using Equations (10), (11), (15), and (17).

Step 5. Let δ is a pre-defined small value. If $|\lambda_{A\_h} - \lambda_{A\_h,\text{old}}| > \delta\lambda_{A\_h}$ or $|\lambda_{B\_h} - \lambda_{B\_h,\text{old}}| > \delta\lambda_{B\_h}$ or $|\lambda_{db_h} - \lambda_{db\_h,\text{old}}| > \delta\lambda_{db\_h}$, then go to Step 2.

Step 6. The values of λ_{A_h}, λ_{B_h}, and λ_{db_h} converge.

5. Analytic and Simulation Results

Computer simulations have been conducted to verify the analytic results. To ensure simulation results are converged, 200 000 calls are simulated in each simulation. Figure 9 shows that the simulation results and the analytic results are consistent. In the experiments, $(1/\mu) = 3$ min, $\eta = 0.2\mu$ or 2μ, and $\lambda_A : \lambda_B : \lambda_{db} = 1:1:2$. The total traffic load $\rho = (\lambda_A + \lambda_B + \lambda_{db})/\mu$ varies from 20 to 30. The capacities of A-band channels and B-band channels are $C_A = C_B = 20$. The results indicate that the LBCR scheme significantly outperforms the other two schemes when the traffic load is high. For a low user mobility ($\eta = 0.2\mu$ in the example), the LB and LBIH schemes have about the same performance. For a high user mobility ($\eta = 2\mu$), the LB scheme provides significantly higher call incompletion probabilities than the LBIH scheme. The results imply that inter-band handoff for load-balancing is important to PCS systems with high user mobility.

5.1. The effects of dual-band handset percentage and user mobility

Figure 10 shows the effects of dual-band handset percentage (α) and user mobility on the call incompletion probability. The traffic loads in the experiments are 26 and 30; α of the traffic load is dual-band handsets, $(1 - \alpha)/2$ of the traffic load A-band handsets, and the remaining B-band handsets. In all schemes, P_{nc} increases for a high user mobility ($\eta = 2\mu$ in this example). On the other hand, the call incompletion probability P_{nc} decreases as the percentage of dual-band handsets increases. However, P_{nc} drops more rapidly in the LBCR scheme; it drops near to the lowest value when the percentage of dual-band handsets is as low as 25%. For the LBIH scheme, this happens only when the percentage of dual-band handset is as high as 75%. The results imply that channel reassignment is an effective technique to balance the loads of both bands. For the LB scheme with a high user mobility, P_{nc} is much higher than that of the other two schemes even for the case where all handsets are dual-band ($\alpha = 100\%$). This is because for a high user mobility, a handset experiences more handoffs; however, a handoff call is restricted to use the

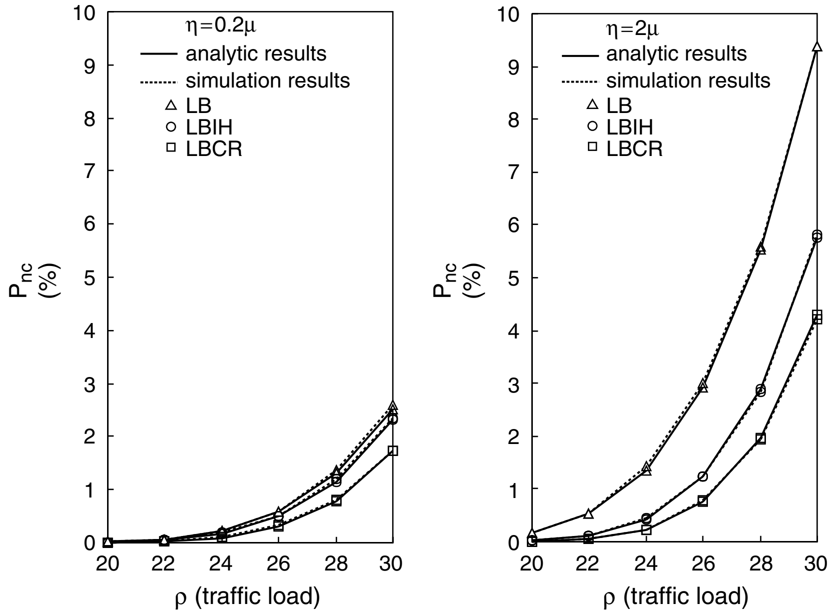


Fig. 9. The call-incompletion probability with 50% dual-band load ($\mu = 1/3$, $\lambda_A : \lambda_B : \lambda_{db} = 1:1:2$).

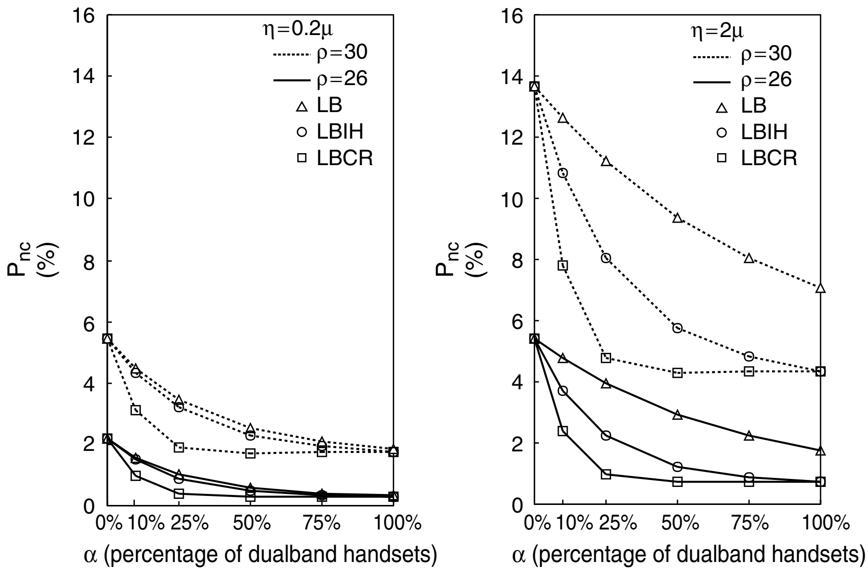


Fig. 10. The effects of dual-band traffic load ($\mu = 1/3$, $\lambda_A : \lambda_B = 1:1$).

same band in the LB scheme. As a result, the call is more likely to be forced to terminate. The results imply that if the percentage of dual-band handset is low, the LBCR scheme should be used. If the percentage of dual-band handsets is high, the LBIH scheme can be used to reduce the overhead of channel reassignment.

Table 1 shows the maximum carried load when the system is engineered to operate at $P_{nc} \leq 2\%$. Note that the improvement of the LBCR over the LB is significant when the percentage of dual-band handsets is low or the user mobility is high. The improvement could be as high as 15% for the case where $\eta = 2\mu$ and $\alpha = 25\%$.

5.2. The comparison between single-band and dual-band users

Figure 11 shows the call-incompletion probabilities of single-band and dual-band users. The call-incompletion probabilities of single-band handsets are significantly higher than those of dual-band handsets in the LB and LBIH schemes. The P_{nc} of the dual-band handsets with high mobility in the LB scheme is clearly higher than that with low mobility. This is because the handoff calls cannot switch between bands. On the other hand, for the LBCR scheme, the call incompletion probabilities of single-band and dual-band handsets converge when the percentage of dual-band handsets is larger than 25%. This is true for both low user mobility and high mobility. The results indicate that the channel re-assignment scheme provides fairness in channel assignment to both single-band and dual-band handsets.

5.3. The overhead of band-switching and forced band-switching

Figure 12 shows the effects of the percentage of dual-band handsets and user mobility on the band-switching rate R_{bs} and probability P_{bs}. The traffic load (ρ) is 30. On call origination or call termination of a dual-band handset, the handset is instructed to switch to the selected band if it does not tune to the band. It is clear that R_{bs} increases as the percentage of dual-band handsets increases. However, the band-switching probabilities P_{bs} decreases as the percentage of dual-band handsets increases, because more dual-band handsets lead to a higher probability that the loads of two bands are balanced. For the LB scheme, R_{bs} and P_{bs} of the users with high mobility are significantly larger than those with low mobility, when α is large. This can be explained as follows. The calls with high mobility experience more handoffs. Since handoff calls do not perform band-switching in the LB scheme, more handoff calls result in a higher probability that the loads of two bands are unequal. As a result, R_{bs} and P_{bs} increase as user mobility increases. For the LBIH and LBCR schemes, the user mobility has no effects on R_{bs} and P_{bs}, because handoff calls can perform band-switching for load-balancing in both schemes.

Figure 13 shows the effects of user mobility and traffic load on the forced band-switching rate R_{fs} and probability P_{fs} in the LBCR scheme. On the channel request of a single-band handset, if there is no free channel in the requested band, an active dual-band handset tuning to the band is selected and forced to switch to the other band. Figure 13(a) shows that R_{fs} increases as the user mobility or the traffic load increases. Since high user mobility leads to more handoffs, the forced band-switching rate R_{fs}

Table 1. The carried load when the system is engineered at $P_{nc} = 2\%$.

Mobility	Percentage of dual-band traffic load (α)	LB	LBIH	LBCR
$\eta = 2\mu$	25% dual-band	24.03	25.72	27.65
	50% dual-band	24.96	27.08	28.03
	75% dual-band	25.78	27.70	28.03
$\eta = 0.2\mu$	25% dual-band	28.00	28.32	30.14
	50% dual-band	29.24	29.55	30.44
	75% dual-band	29.88	30.12	30.44

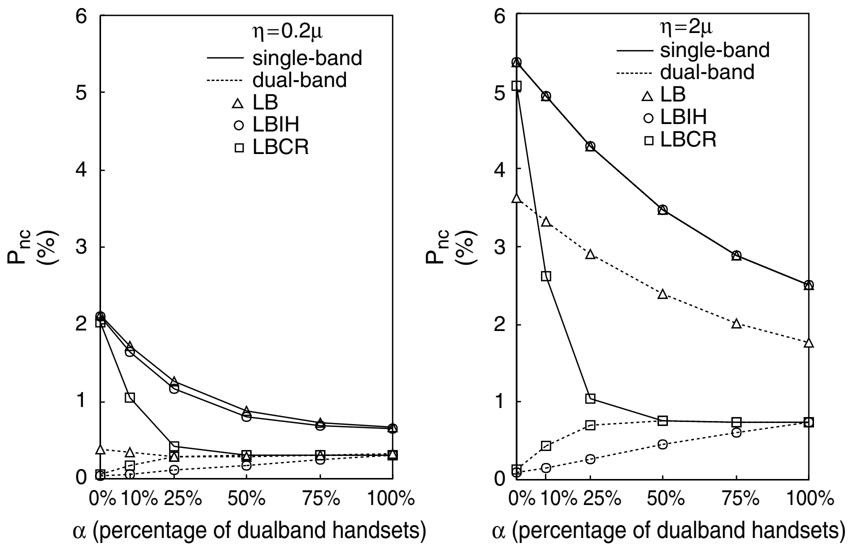


Fig. 11. The call-incompletion probability of single-band and dual-band users ($\mu = 1/3$, $\lambda_A : \lambda_B = 1:1$, $\rho = 26$).

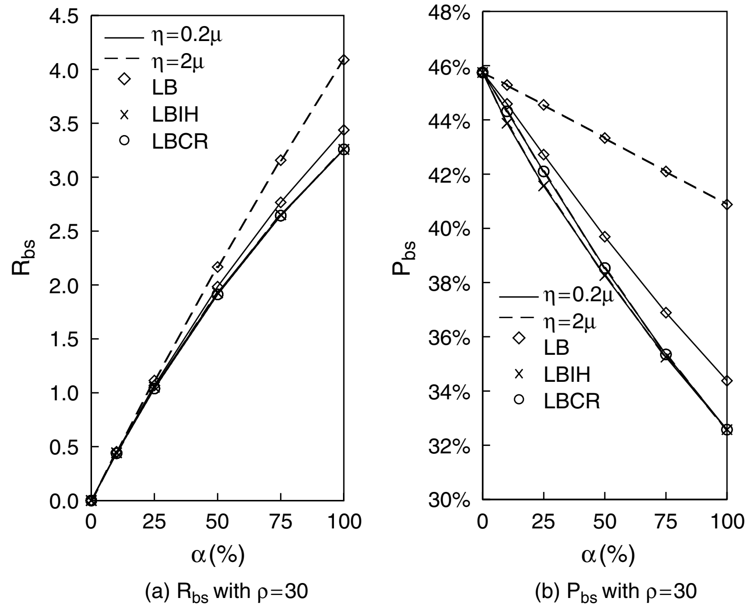


Fig. 12. The effects of the percentage of dual-band handsets and user mobility on R_{bs} and P_{bs} ($\mu = 1/3$, $\lambda_A : \lambda_B = 1:1$).

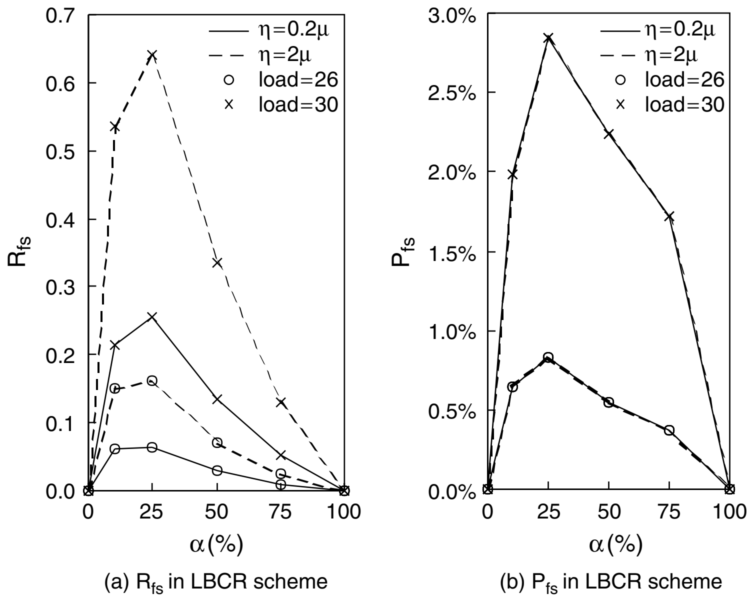
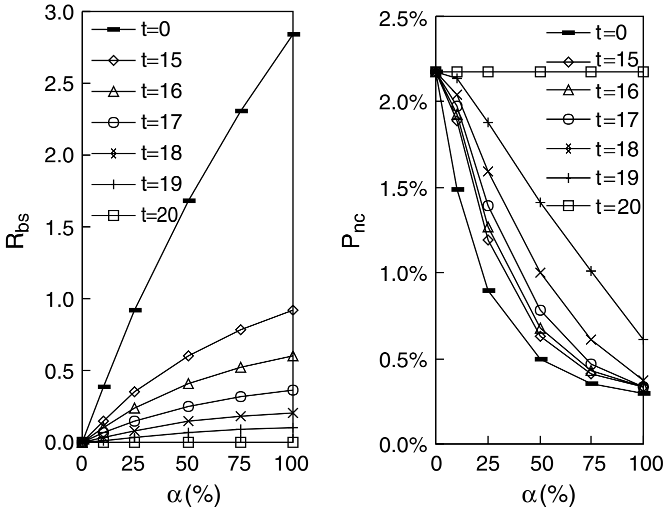


Fig. 13. The effects of user mobility and traffic load on R_{fs} and P_{fs} ($\mu = 1/3$, $\lambda_A : \lambda_B = 1:1$).

increases as η increases. In addition, R_{fs} and P_{fs} increase as the traffic load increases, because higher traffic load results in a higher probability that all channels in a band are occupied. The effects of the percentage of dual-band handsets on R_{fs} and P_{fs} are mixed. For small α, R_{fs} and P_{fs} increases as α increases, because the probability of finding a dual-band victim increases as the number of active dual-band handsets increases. For large α, R_{fs} and P_{fs} decrease as α increases, because the probability that the number of free channels in A-band is equal to that in B-band increases.

5.4. The effects of the band-switching threshold

Figure 14 shows the effects of the band-switching threshold (to activate load-balancing band-selection) on R_{bs} and P_{nc} for the LBIH scheme. In the



(a) The effects of t on R_{bs} (a) The effects of t on P_{nc}

Fig. 14. The R_{bs} and P_{nc} with $t = 0$, 15–20 for the LBIH scheme ($\mu = 1/3$, $\lambda_A : \lambda_B = 1:1$, $\rho = 26$).

experiment, the system traffic load is 26, the user mobility is $\eta = 0.2\mu$, and the band-switching threshold t varies as 0 and 15–20. For $t = 0$, it is the original LBIH scheme. It is clear that R_{bs} decreases as the band-switching threshold increases, because fewer band-switchings are performed. However, this reduction on band-switching overhead is obtained at the cost of a higher call incompletion probability P_{nc} as shown in Figure 14(b); P_{nc} increases as the band-switching threshold increases. Compare the results of the cases where $t = 0$ and $t = 16$. It is interesting to note that R_{bs} decreases significantly while P_{nc} increases only modestly, especially when α is large. The results indicate that the band-switching threshold can be carefully selected such that the band-switching overhead is significantly reduced at the cost of increasing the call incompletion probability by a small amount. Although the experiment results are not presented in this paper, the band-switching threshold has the same effects on reducing the signal overhead of the LB and LBCR schemes.

5.5. The effects of cell residence time and call holding time variances

We investigated the effects of the variances of cell residence time and call holding time on P_{nc}. Gamma distribution is used to generate the cell residence time and call holding time. In the computer simulation experiments, the mean values of the cell residence time and call holding time were fixed, but their variances changed. The probability density function of a Gamma distribution is

$$f(x) = \frac{\alpha}{\Gamma(\gamma)}(\alpha x)^{\gamma-1}e^{-\alpha x}, \text{ for } x > 0$$

The mean of the distribution is γ/α, the variance is γ/α^2, and the coefficient of variation is $v = 1/\sqrt{\alpha}$. The results in Figure 15(a) show that for the high mobility case ($\eta = 2\mu$), as the cell residence time variance increases, P_{nc} increases. This is because when cell residence time variance is large, handsets may experience a large number of handoffs and thus are more likely to be forced to terminate. For the low mobility case, the cell residence time variance has insignificant effect on P_{nc}. This is because the handset mobility is so low that most calls experience no handoff. The results in Figure 15(b) show that for the high mobility, as the call holding time variance increases, P_{nc} decreases. This is because when call holding time variance is large, handsets may experience a large number of short calls and less handoffs, and thus are more likely to complete the calls. For the low mobility, the call holding time variance has an insignificant effect on P_{nc}. This is because the handset mobility is so low that most calls (especially for short calls) experience no handoff.

6. Conclusion

This paper studied the channel assignment problem of dual-band PCS systems where single-band and

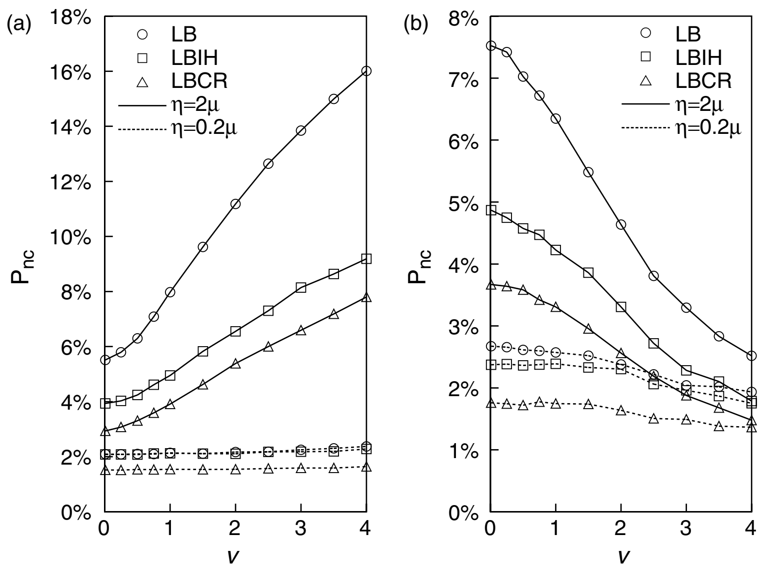


Fig. 15. Effects on (a) the cell residence time and (b) the call holding time variances on P_{nc}.

dual-band handsets co-exist. Three load-balancing channel assignment schemes were proposed in this paper. Analytic models and computer simulation are developed to evaluate the channel assignment schemes. Our experiments show the following results.

- Both the load-balancing and channel re-assignment strategies are effective in increasing the system carried traffic. If the percentage of dual-band handsets is low ($\alpha < 50\%$), both strategies should be applied, i.e., the LBCR scheme should be used. If the percentage is high ($\alpha > 75\%$), the LBIH scheme, which applies the load-balancing technique only, can be used.
- The LBCR scheme provides fairness in channel assignment to single-band and dual-band handsets when α is larger than 25%. In this case, both single-band and dual-band handsets experience about the same call incompletion probability.
- The band-switching overhead increases as the percentage of dual-band handsets and the traffic load increase. The experiment results show that the band-switching threshold can reduce the band-switching overhead at the cost of increasing the call incompletion probability by a small amount.
- The system performance of the dual-band system is affected by the variances of the cell residence time and the call holding time. The experiment results show that when the cell residence time variance is small or the call holding time variance is large, the system provides a low call incompletion probability.

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