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A reservation-based call admission control scheme and system modeling in 4G vehicular networks

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Abstract

In 4G cellular networks, call admission control (CAC) has a direct impact on quality of service (QoS) for individual connections and overall system efficiency. Reservation-based CAC schemes have been previously proposed for cellular networks where a certain amount of system bandwidth is reserved for high-priority calls, e.g., hand-off calls and real-time new calls. Traditional reservation-based schemes are not efficient for 4G vehicular networks, as the reserved bandwidth may not be utilized effectively in low hand-off rates. We propose a channel borrowing approach in which new best effort (BE) calls can borrow the reserved bandwidth for high-priority calls. Later, if a hand-off call arrives and all the channels are busy, it will pre-empt the service of a borrower BE call if there exists any. The pre-empted BE calls are kept in a queue and resume their service whenever a channel becomes available. The analytical model for this scheme is a mixed loss-queueing system for which it is difficult to calculate call blocking probability (CBP) and call dropping probability (CDP). Our focus in this paper is on the system modeling and performance evaluation of the proposed scheme. We present two system models that approximate the operation of the proposed scheme. For these models, we derive the CBP and CDP analytically. It is shown that our analytical results are very close to the ones obtained from simulations. Furthermore, it is observed that our channel borrowing approach decreases the CBP considerably while increases the CDP slightly over a large range of hand-off rates.

Keywords: Reservation-based call admission control; Channel borrowing; CBP and CDP

1 Introduction

Initially, vehicular networks are introduced to provide communications for safety applications such as collision avoidance, hard braking warnings, accident reporting, intersection announcements, etc. Safety applications often require fast message exchanges but do not use much bandwidth where vehicles are enabled to communicate with one another, i.e., vehicle-to-vehicle or vehicle-to-roadside communications. On the other hand, evolution of vehicular networks is aimed to support non-safety multimedia applications which require high-speed Internet for mobile users. Fortunately, the telecommunication industry landscape for cellular networks is growing rapidly from 2G to 4G to accommodate the increasing usage of multimedia applications and users' mobility. In

4G, Worldwide Interoperability for Microwave Access (WiMAX) and Long-Term Evolution (LTE) are two emerging broadband wireless technologies aimed to provide high-speed Internet of 100 Mbps at a vehicular speed of up to 350 km/h [1,2]. Recently, research on the performance evaluation and improvement of 4G/5G vehicular networks has been under the focus of researchers in the filed of vehicular networking [3,4].

In 4G vehicular networks, call admission control (CAC) is considered as one of the radio resource management (RRM) functionalities and has a direct impact on quality of service (QoS) for individual connections and overall system efficiency. The goal of the CAC mechanism is to regulate the admission of new users, while controlling the quality of current connections without any call drops. In the traditional mobile networks, e.g., cellular and vehicular networks, CAC schemes have been designed to handle the voice traffic. On the other hand, design of practical and efficient CAC schemes for 4G vehicular networks is a

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challenging task due to the heterogeneous nature of multimedia traffic, user mobility, etc. However, CAC design is left open for innovation in 4G wireless network standards, such as WiMAX and LTE.

In the design of CAC schemes, the most common QoS parameters for performance evaluation are call blocking probability (CBP) and call dropping probability (CDP). Call blocking means denying new calls due to insufficient bandwidth in the network or the QoS requirements. Call dropping means dropping an existing call during a hand-off process due to users' mobility (vehicular or pedestrian). Forced termination of a call in progress is more frustrating than blocking a new call. As a result, hand-off calls are treated differently by being given a higher priority over new calls in cellular/vehicular networks. Particularly, we may either reserve certain amount of channels from the total available channels in a cell for hand-off calls or dynamically allocate channels for an individual cell, based on the time-varying status of vehicular traffic. The amount of channel reservation for hand-off calls is mostly based on users' mobility pattern, i.e., using vehicular traffic modeling that aggregates variables such as traffic density, mean speed, etc. [5]. In various research efforts on mobile cellular networks, the hand-off call arrival rate can be derived from the mobility models [6-9]. CAC designs based on mobility and traffic models will be *depended* on the assumptions made in modeling of the *users' mobility and traffic pattern.* In vehicular networks, due to the fast movement of vehicles, the variation range of hand-off rates is large. A good CAC design for 4G vehicular networks should be robust enough to support a vast range of hand-off rates. This motivates us to propose a CAC scheme which is robust enough to support a vast range of hand-off rates. We will propose a CAC scheme that *irrespective of the traffic model and mobility pattern* can improve the CBP considerably while not affecting CDP over a large range of hand-off rates. This motivates application of the proposed scheme for 4G vehicular networks.

The main goal of using conventional reservation-based CAC schemes in the cellular and vehicular networks is to reduce CDP. Although bandwidth reservation for hand-off calls decreases CDP, it also increases CBP in 4G wireless networks due to the inefficient channel utilization. By using reservation, a portion of the bandwidth is always reserved for hand-off calls. Hence, new calls may arrive in the system and are blocked, while reserved channels still exist in the system but are unused. On the other hand, newly originated real-time (high priority) calls should be treated differently to satisfy the high-priority customers in 4G wireless networks. Therefore, we propose the idea of channel borrowing for BE calls which carry non-delay-sensitive traffic. In our approach, new BE calls can borrow channels from the reserved channels for high-priority

(hand-off) calls. Later on, if a hand-off call arrives and there is no channel available in the system, it pre-empts the service of the borrower BE call. The pre-empted BE call is kept inside a queue and resumes its service as soon as a channel becomes free.

It is observed that the model associated to the channel borrowing scheme is a mixed loss-queuing system [10]. To the best of our knowledge, no research has adopted the mathematical model for the channel borrowing scheme with the mixed loss-queuing system. However, it is difficult to mathematically analyze the mixed loss-queuing system. Therefore, the objective of the paper is to mitigate the issue of complicated analysis of the mixed loss-queuing system. To achieve the objective, we propose two system approximations for the mixed loss-queuing model and introduce the Markov chain model associated with each system approximation. In Section 4, we will observe that to solve the first system approximation, we need to solve a system of non-linear equations, whereas for the second approximation, we only need to solve a system of linear equations (which is much simpler and more efficient to solve). We will show through numerical analysis and simulations that our system approximations and the proposed channel borrowing scheme perform closely in terms of CBP and CDP. We also show that the proposed channel borrowing scheme considerably decreases CBP compared with the new call bounding scheme [11] while the amount of increase in CDP is minor. Note that the hand-off dynamics in a cellular network is mostly dependent on users' mobility pattern and traffic modeling that can be represented by aggregate variables such as traffic density, mean speed, etc. [5]. In this paper, our focus would be on *modeling and performance analysis* of a reservation-based CAC scheme in which we assume that the hand-off calls arrive based on a Poisson arrival process. Users' mobility and traffic modeling of the incoming calls are out of the scope of this paper and can be studied in a future work.

The rest of the paper is organized as follows. In Section 2, we review the traditional reservation-based CAC in cellular and vehicular networks. Section 3 presents the system model for conventional bandwidth reservation (new call bounding) scheme and the proposed bandwidth reservation with channel borrowing scheme. In Section 4, we study the performance of the proposed channel borrowing scheme analytically and introduce two system approximations for our channel borrowing scheme. Section 5 illustrates the numerical analysis where we show the effectiveness of the channel borrowing idea. Section 6 presents the conclusions of the paper.

2 Literature review

There has been a great body of research on CAC design reported in the literature [1,5,6,12-18]. In this section, we

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highlight a few important papers that mainly focus on reservation-based schemes in cellular and vehicular networks. The *guard channel* policy was proposed by Hong and Rappaport in [6], in which a certain amount of channels is reserved permanently for hand-off calls only, while the rest of the channels is shared by both new calls and hand-off calls. Given the total number of channels in the system is C, we reserve T channels ($T < C$) for hand-off calls. Hence, if the total number of calls in the system exceeds $C - T$, we do not admit new calls anymore. In this scheme, hand-off calls are given higher priority over new calls to reduce the CDP. The authors in [12] proposed fractional guard channel scheme in which the new calls are admitted with a certain probability. Such a probabilistic call admission prevents the system approaching congestion. In [11], the authors showed that when the service time of new calls and hand-off calls is not identically distributed, the traditional one-dimensional Markov chain cannot be used for performance analysis. In this case, two-dimensional Markov chain models must be invoked. Moreover, they proposed *new call bounding* scheme in which the total number of new calls in the system is restricted to a fixed threshold. Hence, if the total number of channels in the system is C, this scheme reserves T channels for hand-off calls and admits a new call if the total number of new calls in the system is less than $C - T$. In all the reservation-based schemes, a critical parameter is the number of reserved channels for hand-off calls since it provides a tradeoff between minimizing CBP and minimizing CDP. To deal with this problem, several dynamic reservation-based schemes were proposed in the literature, e.g., in [1]. Dynamic reservation-based schemes are not easy to analyze, and simulations are used for their performance evaluation. Researchers have also considered multiple threshold reservation schemes in [13,19]. In multiple threshold CAC design, the complexity is increased for the selection of thresholds and the system performance is unpredictable.

The CAC design for vehicular networks is discussed in [5,15,16], where the vehicular environment and movement has a major impact on the system design. Hence, the macroscopic vehicular modeling (CMVM) was introduced in CAC design in [5] where the macroscopic modeling describes vehicular traffic with aggregate variables such as traffic density, mean speed, etc. In [15], both fixed and dynamic channel assignments are discussed for CAC design. Fixed channel assignment requires extensive frequency planning and maintains a constant frequency reuse distance for all cells implementation. Hence, neighboring cells are allocated with mutually disjoint radio channels to cater for mobile host communications in the cell-specific region. On the other hand, dynamic channel assignment enables the fixed channel allocation methods to maintain a pre-set range of channels allocated to a cell

and then varies based on the users' mobility due to vehicular movement. The CAC proposed in [16] uses fixed channel reuse technique, channel borrowing process, and the speed of the vehicle to reserve the channel for hand-off calls to improve quality of service (QoS) in VANETs. The authors in [14] proposed the idea of channel borrowing for the originating new calls along with the idea of channel adaptation for reserved channels. However, the model in [14] does not distinguish between different classes of new calls. Moreover, there is no notion of call pre-emption by hand-off calls, i.e., if a hand-off call arrives and all the reserved channels are borrowed, the hand-off call will be dropped. This will increase the CDP for hand-off calls. In the proposed scheme in our paper, hand-off calls can pre-empt the service of a borrower BE call. This keeps CDP about the same level while increases the channel utilization efficiency and decreases CBP. The work in [14] does not consider any mathematical modeling, and the effectiveness of the proposed scheme is shown through simulations.

In vehicular networks, the hand-off rate varies fast due to the speed of vehicles. A good CAC design for 4G vehicular networks should be robust enough to *support a vast range of hand-off rates*. Most of the research on handling hand-off in vehicular networks are trying to use the mobility/traffic pattern to enhance the call admission process [5,15,16,20-22]. In our work, we propose the channel borrowing idea which improves the channel utilization of conventional channel borrowing CAC schemes and therefore results in improved CBP while does not affect CDP. In Section 5, it will be shown that by applying our CAC scheme, the amount of improvement in CBP is considerable for a vast range of hand-off rates which motivates its application in 4G vehicular networks. Moreover, we propose a mathematical system modeling and provide an analytical performance evaluation framework for the proposed channel borrowing technique.

3 System model for the conventional and the proposed reservation-based schemes

Different classes of traffic have been defined in 4G wireless mobile networks. For example, WiMAX standard supports five different traffic classes and LTE defines nine traffic classes. A new call belongs to one of the traffic classes defined in the network. Other than the new call arrivals, there exist hand-off calls which are generated in a cell due to the mobility of users into the cell. Note that the hand-off calls have the same traffic classification. Assuming a wireless network with N traffic classes, the Markov modeling of the system will end up to a Markov chain with $2 \times N$-dimensional state space which makes it unfeasible to analyze mathematically. To show the effectiveness of our

proposed reservation-based CAC scheme and to provide an analytical performance evaluation for it, we consider a 4G wireless network with two main priority traffic classes. In our model, we assume that the high-priority class contains only the hand-off calls that is coming from other cells in the cellular network. We may also categorize the real-time new calls in the current cell into this class. The low-priority class contains the new calls generated in the current cell. We assume that the new calls are sub-categorized to non-real-time (nRT) new calls and best effort (BE) new calls. Examples of nRT and BE calls are non-real-time multimedia traffic (e.g., Youtube video) and web traffic, respectively. Example of real-time traffic is live broadcasting.

It is assumed that the arrival processes of hand-off, nRT, and BE calls are Poisson distributed with parameters λ_H, λ_{nRT}, and λ_{BE}, respectively. We further assume that the service processes of the hand-off, nRT, and BE calls are exponentially distributed with parameters μ_H, μ_{nRT}, and μ_{BE}, respectively. The system bandwidth is channelized, and the number of channels (bandwidth units) in the system is C. Note that C is not the network capacity in terms of amount of served traffic (which is dependent on the users' wireless channel model and interference). In this model, C denotes the number of physical network resources in a cell which should be allocated to the arriving calls, e.g., number of physical resource blocks in an LTE network.

We build our channel borrowing idea on the *new call bounding scheme* proposed in [11], and henceforth, we call this CAC as the conventional scheme. We first review the new call bounding scheme and then explain how we incorporate our channel borrowing approach in this scheme.

3.1 Review of new call bounding scheme

In the conventional scheme (i.e., new call bounding scheme introduced in [11]), a new call is blocked if the total number of admitted new calls in the system is more than $C - T$ or there is no more channel available in the system. T denotes the number of channels reserved for high-priority traffic. Note that $T < C$. A hand-off call is blocked only if there is no channel available in the system to serve it. By defining the state of the system as the pair (n_1, n_2) where n_1 and n_2 are the number of hand-off and new calls in the system, respectively, the authors in [11] derived a two-dimensional Markov chain for this system (Figure two in [11]). Since this Markov chain is *time-reversible*, one may easily write the local balancing equations for it and derive the closed-form formulas for CBP of new calls and CDP of hand-off calls (refer to [11], Equations (1) and (2)). Global balance equations also may be used to solve this Markov chain. This is involved in solving a system of linear equations.

3.2 Channel borrowing in reservation-based schemes

In this section, we introduce our channel borrowing approach in the new call bounding scheme. The idea of channel borrowing can be implemented in any reservation-based CAC algorithm. Before we proceed to introduce our CAC scheme, we will clarify our motivations by mentioning the following points:

- Among the new call arrivals, BE calls are the ones that are flexible in terms of QoS requirements. BE traffic is usually dedicated to non-critical services such as web traffic or file transfers. Therefore, the service of a BE call can be delayed or can be disrupted.
- In reservation-based CAC approaches, in cases where the hand-off arrival rate is relatively low and the arrival rate for BE calls is relatively high, the channels statically reserved for hand-off calls may be wasted since we idle the reserved channels and keep them for hand-off calls arriving in future. Hence, the channel utilization in such schemes is not efficient.

By considering the inefficiency of bandwidth utilization in reservation-based schemes and the flexibility of the service of BE calls, we propose the following channel borrowing scheme: We consider a reserved bandwidth of T channels for hand-off calls. We admit an nRT call only if there exists a free channel in the system, and the total number of new calls (nRT and BE) does not exceed $C - T$ (similar to what we do in the new call bounding scheme). However, we allow the BE calls to use all the channels in the system (upon the availability). When admitting a new BE call even if we violate the reservation of hand-off calls, we still admit it if there exists any free channel in the system. Hence, a new BE call can borrow a channel from the reserved channels of hand-off calls. In this case, if in the near future a hand-off call arrives and there is no available channel in the system to serve it while the total number of hand-off calls in the system is less than T calls, the hand-off arrival can pre-empt the service of the borrower BE call. In this case, the BE call returns the borrowed channel. Nevertheless, we do not drop the service of the pre-empted BE call; instead, we will keep the pre-empted BE call in a queue and will resume its service as soon as a channel becomes available. We denote the size of this queue at time t by $X(t)$. At the arrival time of a BE call if $X(t) > 0$, we will block the new BE arrival.

If we denote the number of hand-off calls, nRT calls, and BE calls in the system by n_1, n_2, and n_3, respectively, we have the following properties for the dropping of hand-off calls and blocking of nRT calls and BE calls.

- A hand-off arrival will be dropped if $n_1 + n_2 + n_3 = C$ and $n_1 \geq T$.
- If $n_1 + n_2 + n_3 = C$ and $n_1 < T$, a hand-off arrival will be admitted by pre-empting a BE call.

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- An nRT arrival will be blocked if $n_1 + n_2 + n_3 = C$ or $n_2 + n_3 \geq C - T$.
- A BE arrival will be blocked if $X(t) > 0$ or if $X(t) = 0$ and $n_1 + n_2 + n_3 = C$.

4 Performance analysis of the proposed channel borrowing scheme

In the proposed channel borrowing CAC scheme described above, there is no queue for the hand-off and nRT calls while we keep the pre-empted BE calls in a queue. This CAC system model is a mixed loss-queueing system [10], and therefore, it is not easy to analyze mathematically. In the following section, we will introduce two system approximations for the channel borrowing scheme described in Section 3.2 by using two pure loss systems. We can analyze the approximation systems mathematically by solving the global balance equations for each system. We will show that these two approximation systems perform very closely with respect to the the original mixed loss-queueing system in terms of CBP and CDP.

4.1 System approximation 1

Let $p(n_1, n_2, n_3)$ denote the steady-state probability of being at state (n_1, n_2, n_3). It can be verified that in the proposed channel borrowing CAC scheme, the input arrival rate to the queue keeping the pre-empted BE calls is equal to:

$$\lambda_H \sum_{\substack{n_1+n_2+n_3=C \\ n_1<T}} p(n_1, n_2, n_3), \qquad (1)$$

where $\sum_{\substack{n_1+n_2+n_3=C \\ n_1<T}} p(n_1, n_2, n_3)$ is the probability of the system being in the state that all the channels are utilized while the number of hand-off calls is less than T. In these states, if a hand-off call arrives, it will request a channel borrowed by a BE call previously. Since the hand-off calls arrive with rate λ_H, the total rate of pre-empted BE calls is given by (1).

In the first system approximation, we remove the queue in the system and instead modify the arrival rate of the BE calls to:

$$\lambda_{BE}^{(new)} = \lambda_{BE} + \lambda_H \sum_{\substack{n_1+n_2+n_3=C \\ n_1<T}} p(n_1, n_2, n_3). \qquad (2)$$

As it is observed, the arrival rate $\lambda_{BE}^{(new)}$ depends on the state probabilities and the arrival rate of the hand-off calls. Such a dependency is expected since there is a loop in the system which reenters the pre-empted BE calls into the system. By applying such an approximation, we will get rid of the queue in the system and obtain a pure loss system with a modified BE arrival rate (which is dependent on the system state probabilities). We can derive the

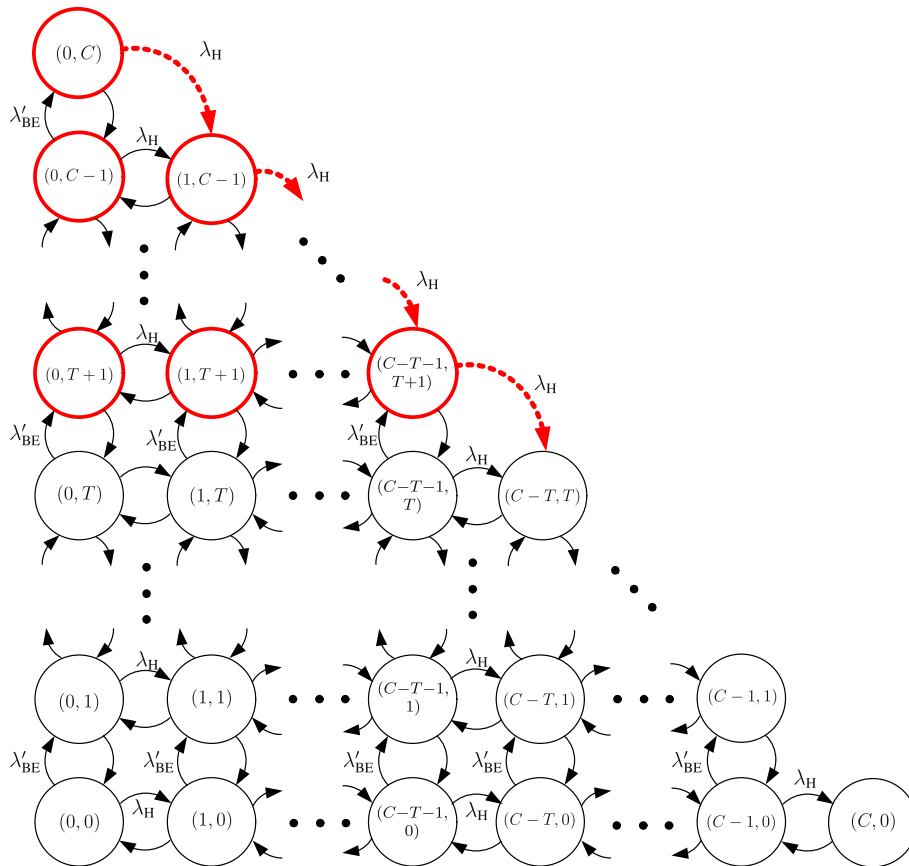three-dimensional Markov chain for this approximation with the state space:

$$\mathcal{S} = \{(n_1, n_2, n_3) \mid n_1, n_3 \geq 0, 0 \leq n_2 \leq C - T, n_1 \quad (3)$$
$$+ n_2 + n_3 \leq C\}.$$

We can check that the transition probabilities for the Markov chain associated to this system approximation are the following:

$$q(n_1, n_2, n_3; n_1, n_2, n_3 - 1) = n_3 \mu_{BE}$$
$$(0 \leq n_1 < C, n_3 > 0, 0 \leq n_2 \leq C - T, n_1 + n_2$$
$$+ n_3 \leq C)$$
$$q(n_1, n_2, n_3; n_1, n_2, n_3 + 1) = \lambda_{BE}^{(new)}$$
$$(0 \leq n_1 < C, 0 \leq n_2 \leq C - T, n_1 + n_2 + n_3 < C)$$
$$q(n_1, n_2, n_3; n_1, n_2 - 1, n_3) = n_2 \mu_{nRT}$$
$$(0 \leq n_1 < C, 0 < n_2 \leq C - T, n_1 + n_2 + n_3 \leq C)$$
$$q(n_1, n_2, n_3; n_1, n_2 + 1, n_3) = \lambda_{nRT}$$
$$(0 \leq n_1 < C, 0 \leq n_2 + n_3 < C - T, n_1 + n_2 + n_3 < C)$$
$$q(n_1, n_2, n_3; n_1 - 1, n_2, n_3) = n_1 \mu_H$$
$$(0 < n_1 \leq C, 0 \leq n_2 \leq C - T, n_1 + n_2 + n_3 \leq C)$$
$$q(n_1, n_2, n_3; n_1 + 1, n_2, n_3) = \lambda_H$$
$$(0 \leq n_1 < C, 0 \leq n_2 \leq C - T, n_1 + n_2 + n_3 < C)$$
$$q(n_1, n_2, n_3; n_1 + 1, n_2, n_3 - 1) = \lambda_H$$
$$(0 \leq n_1 < T, 0 \leq n_2 \leq C - T, n_1 + n_2 + n_3 = C)$$

It is hard to illustrate the three-dimensional Markov chain on paper. If we assume that the nRT class does not exist (or $\lambda_{nRT} = 0$), we will obtain a two-dimensional Markov chain since we will have only two classes of BE and hand-off calls. Note that the idea of channel borrowing is not affected by this simplification and can be still applied without nRT class, since in channel borrowing scheme, a BE call is borrowing a channel from the reserved channels for hand-off calls. Figure 1 depicts the two-dimensional Markov chain associated to this system approximation. The states shown in black are the states that also appear in the conventional new call bounding scheme. The states shown in red are the states that do not exist in the new call bounding scheme, but they appear in the proposed channel borrowing scheme. In this figure, the arrival rate of BE calls is denoted by λ_{BE}'. For the conventional new call bounding scheme, we have $\lambda_{BE}' = \lambda_{BE}$. For the system approximation we introduced in this subsection, we have $\lambda_{BE}' = \lambda_{BE}^{(new)}$.

We use global balance equations and solve the Markov chain numerically. In this system approximation, instead of constant λ_{BE} value, we have to use the new BE arrival rate $\lambda_{BE}^{(new)}$ in the global balance equations. Since $\lambda_{BE}^{(new)}$ is a function of the system states, the global balance equations will result into a system of non-linear equations that should be solved numerically using non-linear solvers.

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Figure 1 Markov chain associated to the new call bounding scheme, system approximations 1 and 2. The black states are the ones appear in the Markov chain of the new call bounding scheme with $\lambda'_{BE} = \lambda_{BE}$. The black and red states appear in the system approximations 1 and 2. For the system approximation 1, we have $\lambda'_{BE} = \lambda_{BE}^{(new)}$, and for system approximation 2, we have $\lambda'_{BE} = \lambda_{BE}$.

To clarify this fact, consider the global balance equation associated to state $(0, C)$ in Figure 1.

$$
\begin{aligned}
p(0, C)(\lambda_H + C\mu_H) &= p(0, C-1)\lambda_{BE}^{(new)} \\
&= \lambda_{BE}\, p(0, C-1) + \lambda_H \sum_{\substack{n_1+n_3=C \\ n_1 < T}} p(0, C-1) p(n_1, n_3)
\end{aligned}
$$

As it is observed, in this equation, we have multiplicative terms $p(0, C-1)p(n_1, n_3)$ which makes it a non-linear equation. As C increases, the size of such a non-linear system of equations increases rapidly. For example, for a system with 16 channels, we obtain a system of non-linear equations with more than 800 variables which may become very time-consuming and inefficient to solve. Therefore, we propose the following system approximation presented in the following subsection which will result in a system of linear equations.

4.2 System approximation 2

In the second system approximation, we assume that $\lambda'_{BE} = \lambda_{BE}$. This is equivalent to assume that the pre-empted BE calls are dropped without being returned to the system inside a queue. Clearly, the accuracy of this approximation is dependent on the rate of pre-emption which itself is dependent on the input arrival rates. Such an approximation will result in a system of *linear* global balance equations. A large system of linear equations can be efficiently solved in a reasonable amount of time. We will show that the first and the second system approximations will result in very close CBP and CDP values. Therefore, for system performance evaluation, we propose to use the second approximation especially for systems with large number of channels (e.g., in realistic wireless systems).

5 Performance evaluation

In this section, we will evaluate the performance of the proposed channel borrowing scheme and compare it with that of the conventional new call bounding scheme in

terms of CBP and CDP. We also validate our system approximations by comparing the derived CDP and CBP values obtained from global balance equations and the CDP and CBP values obtained from simulation of the original mixed loss-queueing model.

First, we show that the two system approximations perform closely in terms of CBP and CDP. To show this, we have derived the CBP and CDP associated to the system approximations 1 and 2 by solving the global balance equations numerically. The CBP and CDP values for these approximations are calculated then as follows:

$$
\begin{aligned}
\text{CBP} = & \sum_{(n_1,n_2,n_3):n_2+n_3 \geq C-T} \frac{\lambda_{\text{nRT}}}{\lambda_{\text{nRT}} + \lambda'_{\text{BE}}} p(n_1, n_2, n_3) \\
& + \sum_{\substack{(n_1,n_2,n_3):n_2+n_3 \geq C-T \\ n_1+n_2+n_3=C}} \frac{\lambda'_{\text{BE}}}{\lambda_{\text{nRT}} + \lambda'_{\text{BE}}} p(n_1, n_2, n_3) \\
& + \sum_{\substack{(n_1,n_2,n_3):n_2+n_3 < C-T \\ n_1+n_2+n_3=C}} p(n_1, n_2, n_3) \qquad (4)
\end{aligned}
$$

$$
\text{CDP} = \sum_{\substack{(n_1,n_2,n_3):n_2+n_3 < C-T \\ n_1+n_2+n_3=C}} p(n_1, n_2, n_3) \qquad (5)
$$

The CBP for system approximation 1 is calculated if in (4) we put $\lambda'_{\text{BE}} = \lambda_{\text{BE}}^{(\text{new})}$ and is calculated for system approximation 2 if we put $\lambda'_{\text{BE}} = \lambda_{\text{BE}}$. To compare the analytical results for system approximations 1 and 2, we considered a system with $C = 12$ and $T = 6$ and solved the global balance equations using Matlab. Solving the global balance equations for system approximation 1 with more than 12 channels takes a considerable amount of time, and therefore, we did the numerical analysis only for $C = 12$. The service rates of hand-off, BE, and nRT traffic are given by $\mu_{\text{H}} = \mu_{\text{BE}} = \mu_{\text{nRT}} = 1$. We also assume that the arrival rate of nRT traffic is $\lambda_{\text{nRT}} = 0.5$. We plot the CBP and CDP for $\lambda_{\text{H}} = 0.5 \times i$ and $\lambda_{\text{BE}} = 0.5 \times i$ where $i = 1, 2, \ldots, 10$. The parameters of the numerical analysis for comparing the performance of approximations 1 and 2 are presented in Table 1. Figure 2a,b shows the results in 3D graphs. As we observe in the figures, the two system approximations will result in very close CBP and CDP values. The CBP and CDP values of the system approximation 2 are slightly lower than that of the system approximation 1, since in system approximation 2, we will drop all the pre-empted BE calls, and therefore, the BE load in the system approximation 2 is slightly smaller than that of the system approximation 1. As a result, the system approximation 2 is suggested for the performance evaluation for large networks (with large amount of channels).
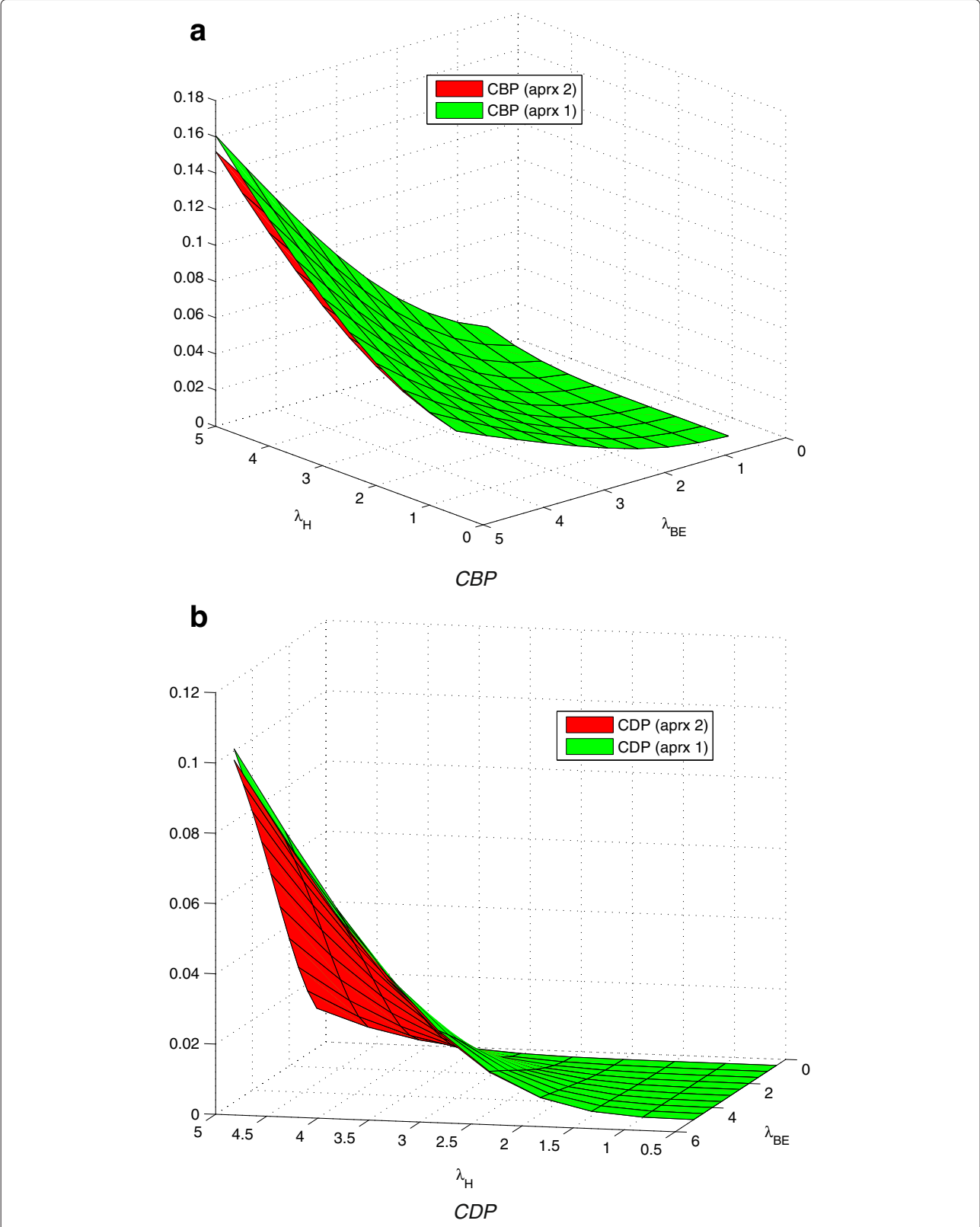
As explained earlier, we used system approximations 1 and 2 to derive approximate values of CDP and CBP

Table 1 Parameter setting in numerical analysis for comparing the performance of approximations 1 and 2

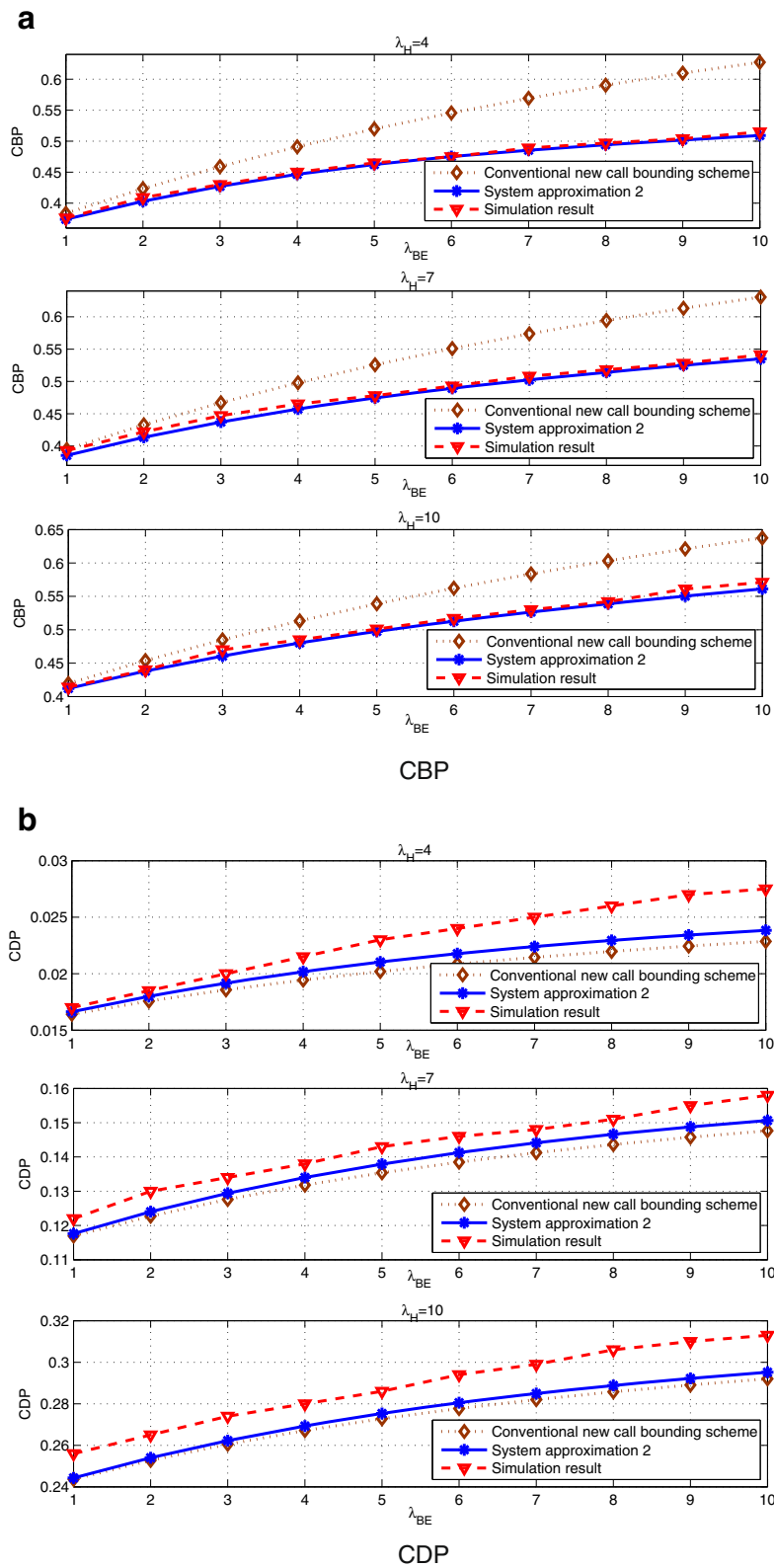| Parameter	Setting
Number of channels (C)	12
Reserved channels (T)	4
$\mu_{\text{H}}, \mu_{\text{BE}}, \mu_{\text{nRT}}$	1
λ_{nRT}	0.5
λ_{H}	$0.5 \times i, i = 1, 2, \ldots, 10$
λ_{BE}	$0.5 \times i, i = 1, 2, \ldots, 10$

for the original mixed loss-queueing model which implements the proposed bandwidth borrowing scheme. It is due to the fact that analytical derivation of the CDP and CBP of the original mixed loss-queueing model is unfeasible. Therefore, we invoked simulations to derive those values. The simulations and the analytical study are performed both in Matlab. To show how precise are our approximations and to compare the analytical results with the simulation results for the proposed bandwidth borrowing scheme and then with the conventional scheme, a system with $C = 16$ and $T = 8$ is considered. In comparison, the CDP and CBP values are calculated for the system approximation 2 by solving the system of global balance (linear) equations. We also perform simulation of the original mixed loss-queueing model to derive the actual CDP and CBP values of the proposed channel borrowing scheme. The CDP and CBP values of the conventional scheme are also calculated based on the results in [11]. The CBP and CDP values are calculated for $\lambda_{\text{H}} = 4, 7, 10$ and $\lambda_{\text{BE}} = i$ where $i = 1, 2, \ldots, 10$. We present the results for two values of $\lambda_{\text{nRT}} = 10$ and $\lambda_{\text{nRT}} = 1$ in Figures 3 and 4, respectively. Parameter setting for the analysis of this part are summarized in Table 2.

From the CBP performance results, it is evident that the channel borrowing scheme results in a considerable decrease in CBP compared with the conventional bandwidth reservation scheme. Similarly, the CDP in the channel borrowing scheme is slightly lower than that of the conventional bandwidth reservation scheme. Conversely, the channel borrowing scheme admits more BE calls for the unused reserved channel and then keeps the pre-empted ones in a queue to resume their service once the channel is available. Therefore, more BE calls are using the unreserved channels, and less hand-off calls have the opportunity to use the unreserved channels. This makes the probability of the call dropping of hand-off calls increases. However, the amount of increase for CDP in the proposed channel borrowing scheme is very small compared to the gain obtained in terms of the CBP decrease. For example, for $\lambda_{\text{H}} = 4$, $\lambda_{\text{nRT}} = 10$, and $\lambda_{\text{BE}} = 10$, the CBP of the proposed scheme is 0.11 less than that

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Figure 2 CBP and CDP performance of system approximations 1 and 2 for a system with $C = 12$, $T = 6$, and $\lambda_{nRT} = 0.5$. **(a)** CBP and **(b)** CDP.

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Figure 3 CBP and CDP performance of the system for simulation, approximation 2, and the conventional scheme with $C = 16$, $T = 8$, and $\lambda_{nRT} = 10$. **(a)** CBP and **(b)** CDP.
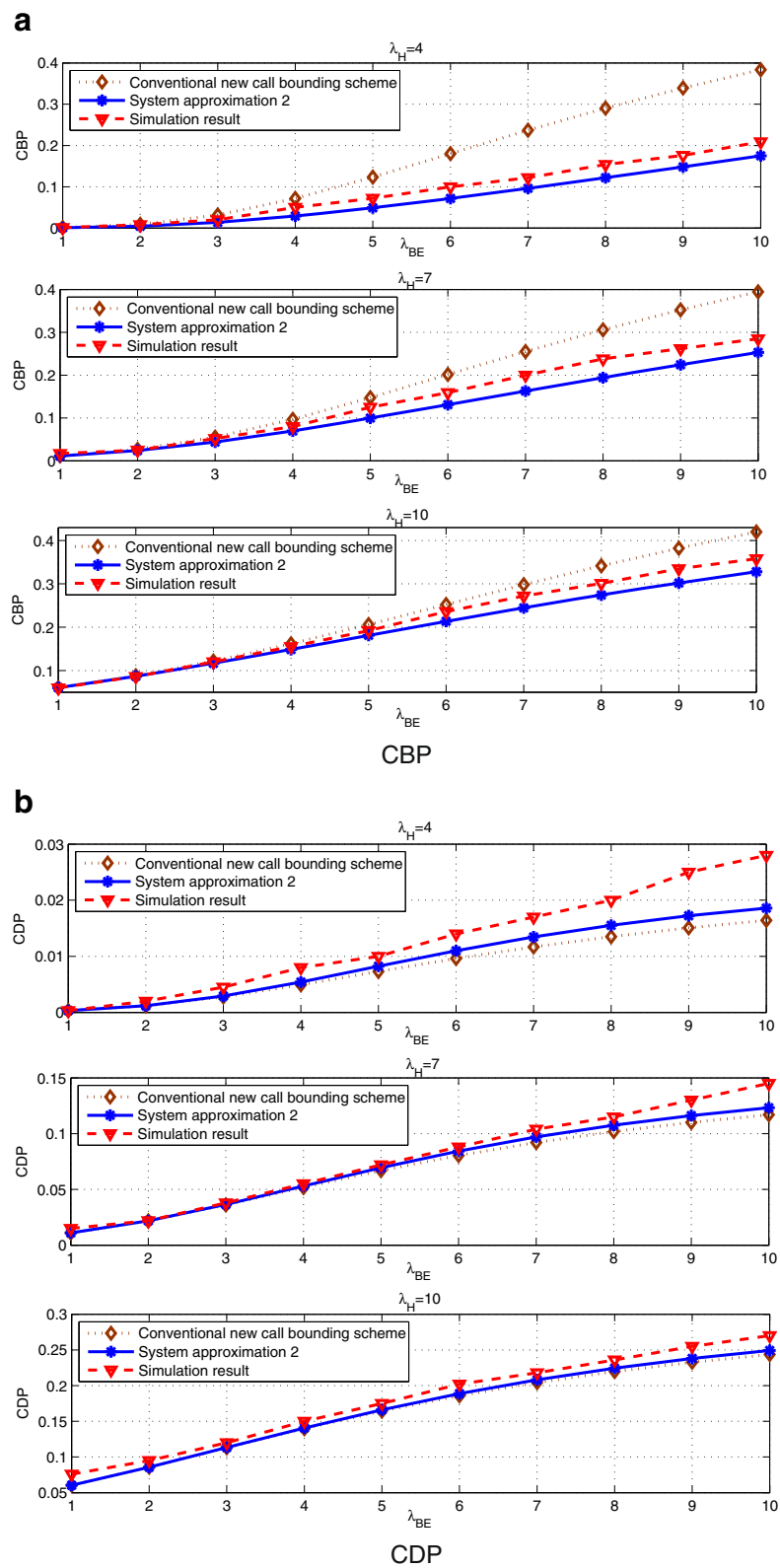
Figure 4 CBP and CDP performance of the system for simulation, approximation 2, and the conventional scheme with $C = 16$, $T = 8$, and $\lambda_{nRT} = 1$. **(a)** CBP and **(b)** CDP.

Table 2 Parameter setting for comparing the performance of simulation and approximations 2 and the conventional scheme

Parameter	Setting
Number of channels (*C*)	16
Reserved channels (*T*)	8
$\mu_H, \mu_{BE}, \mu_{nRT}$	1
λ_{nRT}	1, 10
λ_H	4, 7, 10
λ_{BE}	$i = 1, 2, \ldots, 10$

of the conventional scheme, while the CDP of the conventional scheme is 0.004 less than that of the channel borrowing scheme. Another example is the case $\lambda_H = 4$, $\lambda_{nRT} = 1$, and $\lambda_{BE} = 10$ where CBP of the proposed borrowing scheme is 0.175 less than that of the conventional scheme while the difference of CDP values in these two schemes is 0.012. Also, the simulation results show that the system approximation 2 performs very closely to the original mixed loss-queuing system. Thus, we propose to use this approximation for system performance evaluation of channel borrowing scheme in reservation-based CAC schemes.

Since solving the set of non-linear equations for a system with more than 12 servers is very time-consuming, we used the system approximation 2 (the one with linear equations) for our analytical study. Therefore, when we compare the analytical results with the simulation results (simulation of the borrowing idea in a mixed loss-queueing model), we only considered system approximation 2. Note that system approximation 2 is a more relaxed system approximation (with respect to approximation 1) for the mixed loss-queueing model since in the second approximation, we assume that the pre-empted BE calls are dropped. By comparing the CDP and CBP derived from simulation of the original mixed loss-queueing model with those of the system approximation 2 and the conventional reservation-based CAC scheme, we conclude the following:

- The proposed channel borrowing idea outperforms the conventional reservation-based CAC scheme. This is concluded by comparing the simulation results of the proposed scheme with the conventional scheme.
- The system approximation 2 can provide reasonably close CDP and CBP values for the mixed loss-queueing model.

System approximation 1 is expected to even perform better than the approximation 2. However, due to its computational overhead, it is not desirable.

Finally, we observe that the CBP improvement is observable for a vast range of hand-off rates (4, 7, and 10) which implies that the proposed CAC scheme is robust enough to support high and low hand-off rates which motivates the application of the proposed scheme in 4G vehicular networks.

6 Conclusions

In this paper, we introduced the idea of channel borrowing for reservation-based CAC schemes. The lack of efficiency in bandwidth utilization is the main motivation to use this idea in reservation-based CAC schemes. In our approach, BE calls are able to borrow channels from the reserved channels for hand-off calls. A hand-off arrival call can pre-empt the service of a borrower BE call, and the pre-empted BE calls are stored in a queue to resume their service in future. Moreover, we modeled the channel borrowing scheme using a mixed loss-queuing system and introduced two system approximations for the proposed borrowing scheme to simplify the mathematical analysis. By using simulations and numerical analysis, we showed that the two approximations result in very close CBP and CDP values with respect to the actual CBP and CDP values. Furthermore, it was shown that channel borrowing decreases CBP considerably while it only increases CDP slightly. In our study, the number of reserved channels for high-priority calls, i.e., *T*, is assumed to be fixed. Optimization of *T* with respect to the number of users in the cell and the arrival rate of high-priority calls can be consider as a future work in this area of research.

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